Draft

Geologic Technical Report

Shasta Lake Water Resources Investigation, California

Prepared by:

United States Department of the Interior
Bureau of Reclamation
Mid-Pacific Region

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Abbreviations and Acronyms

Alquist-Priolo Act	Alquist-Priolo Earthquake Fault Zoning Act
Bay Area	San Francisco Bay Area
Bay-Delta	San Francisco Bay/Sacramento-San Joaquin Delta
CDMG	California Division of Mines and Geology
cfs	cubic feet per second
CVP	Central Valley Project
DCC	Delta Cross Channel
Delta	Sacramento-San Joaquin Delta
EIR	Environmental Impact Report
EIS	Environmental Impact Statement
FSSC	Forest Service Site Class
HUC	Hydrologic Unit Code
msl	mean sea level
NRA	National Recreational Area
PGA	peak ground acceleration
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
RBPP	Red Bluff Pumping Plant
SLWRI	Shasta Lake Water Resources Investigation
STATSGO	State Soil Geographic Database
STNF	Shasta-Trinity National Forest
SWP	State Water Project
UBC	Uniform Building Code
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey

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Chapter 1
Affected Environment

This chapter describes the affected environment related to geology, seismicity, soils and erosion, mineral resources and geomorphology for the dam and reservoir modifications proposed under the Shasta Lake Water Resources Investigation (SLWRI).

The evaluation in this technical report is based on a review of existing literature and data, along with information obtained from field investigations performed to support the SLWRI (e.g., shoreline erosion surveys, wetland delineation, and geotechnical investigations and surveys). The information included in the technical analysis is also derived from the following sources:

- CALFED Bay-Delta Program Final Programmatic Environmental Impact Statement (EIS)/Environmental Impact Report (EIR) (CALFED 2000a).
- Contra Costa Water District Alternative Intake Project Draft EIS/EIR (CCWD 2006).
- North-of-the-Delta Offstream Storage Investigation Initial Alternatives Information Report (DWR and Reclamation 2006).

1.1 Environmental Setting

For purposes of the SLWRI, the project study area has been divided into a primary study area and an extended study area. The primary study area has been further divided into Shasta Lake and vicinity and upper Sacramento River (Shasta Dam to Red Bluff). Shasta Lake and vicinity consists of lands immediately upstream from Shasta Dam, including the bed of Shasta Lake up to 1,090 feet above mean sea level (msl), which would be the gross pool elevation if the highest dam raise being considered – a raise of 18.5 feet – were implemented. Also included in the Shasta Lake and vicinity portion of the primary study area are lands above the 1,090-foot msl topographic contour which would be physically disturbed as a result of the action. These lands consist of borrow areas and areas proposed for relocation of existing uses and infrastructure including roads, bridges, buried and aboveground utilities, campgrounds, and protective dikes. Where additional specificity enhances the analyses, this technical report also references seven “arms” within Shasta Lake. Five arms are defined by the major drainages that flow into Shasta Lake: Big Backbone Creek, the Sacramento River, the McCloud River, Squaw Creek, and the Pit River. Two arms – Main Body East Arm and Main Body West Arm –

reference subdivisions of the main body of the lake that are not as well defined by drainage pattern (see Figure 1-1).

The primary study area is located in both Shasta and Tehama Counties, and includes Shasta Dam and Reservoir. All major and minor tributaries to the reservoir, and a corridor along the Sacramento River downstream to the Red Bluff Pumping Plant (RBPP), are also within the primary study area.

The extended study area extends from the RBPP south (downstream along the Sacramento River) to the Sacramento–San Joaquin Delta (Delta). Besides the Sacramento River, it also includes the San Francisco Bay/Sacramento–San Joaquin Delta (Bay-Delta) area, and the facilities and the water service areas of the Central Valley Project (CVP) and State Water Project (SWP). This extended study area includes CVP and SWP reservoirs and portions of tributaries that are downstream from these reservoirs and affect Sacramento River and Delta flows. These reservoirs and tributaries include Lake Oroville, Folsom Lake, San Luis Reservoir, New Melones Reservoir, and Trinity Reservoir, and portions of the Trinity, Feather, American, and Stanislaus Rivers. The CVP and SWP water service areas include much of the Sacramento and San Joaquin valleys, and substantial portions of the San Francisco Bay Area (Bay Area) and Southern California.

1.1.1 Geology

The geology of the study area is described below for both the primary and extended study areas. The bedrock geology of the study area is described in the following paragraphs. The boundaries of the geomorphic provinces referenced in this technical report are presented in Figure 1-2. A geologic timescale is presented in Table 1-1 as a reference for ages of formations described in this chapter.

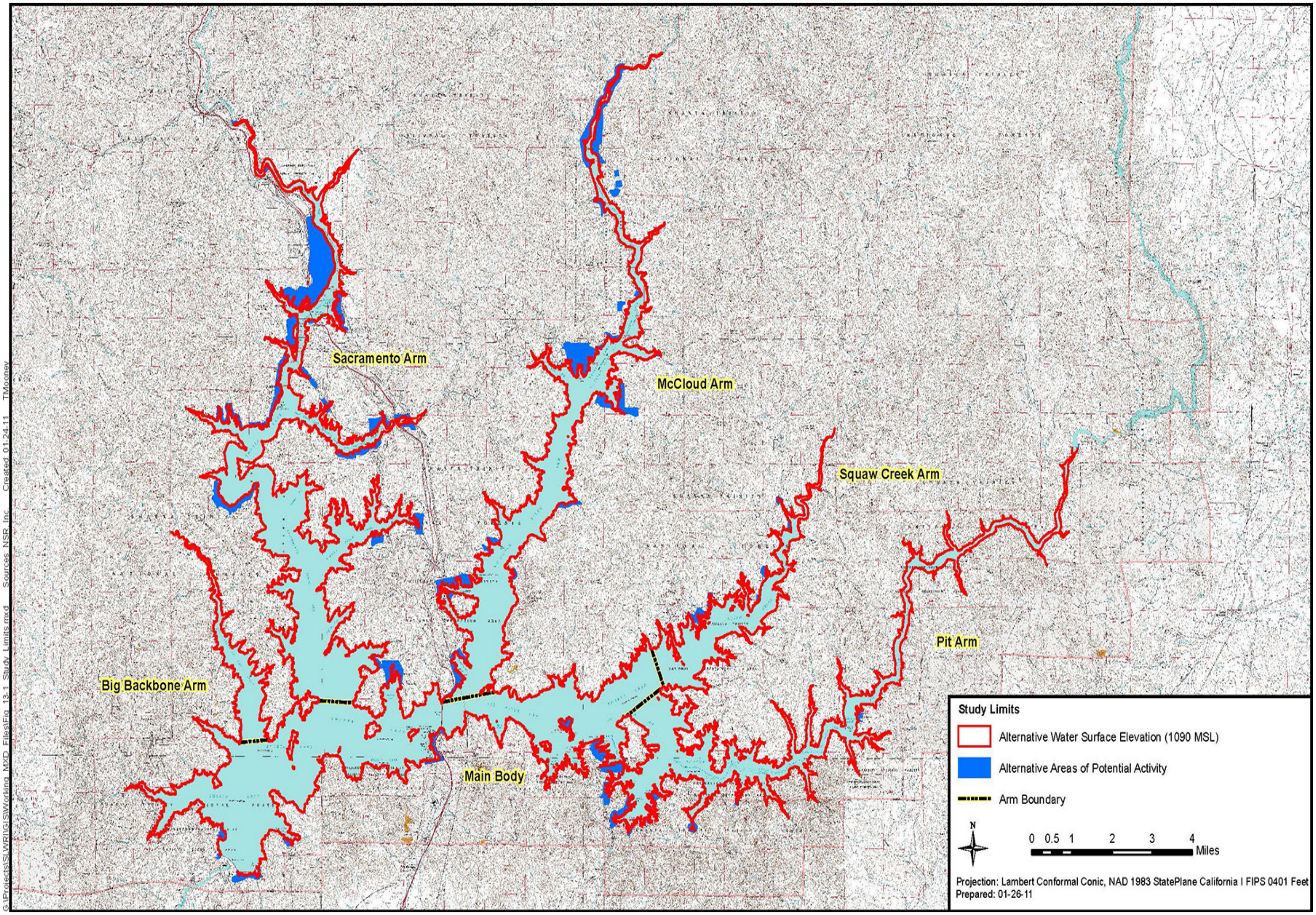
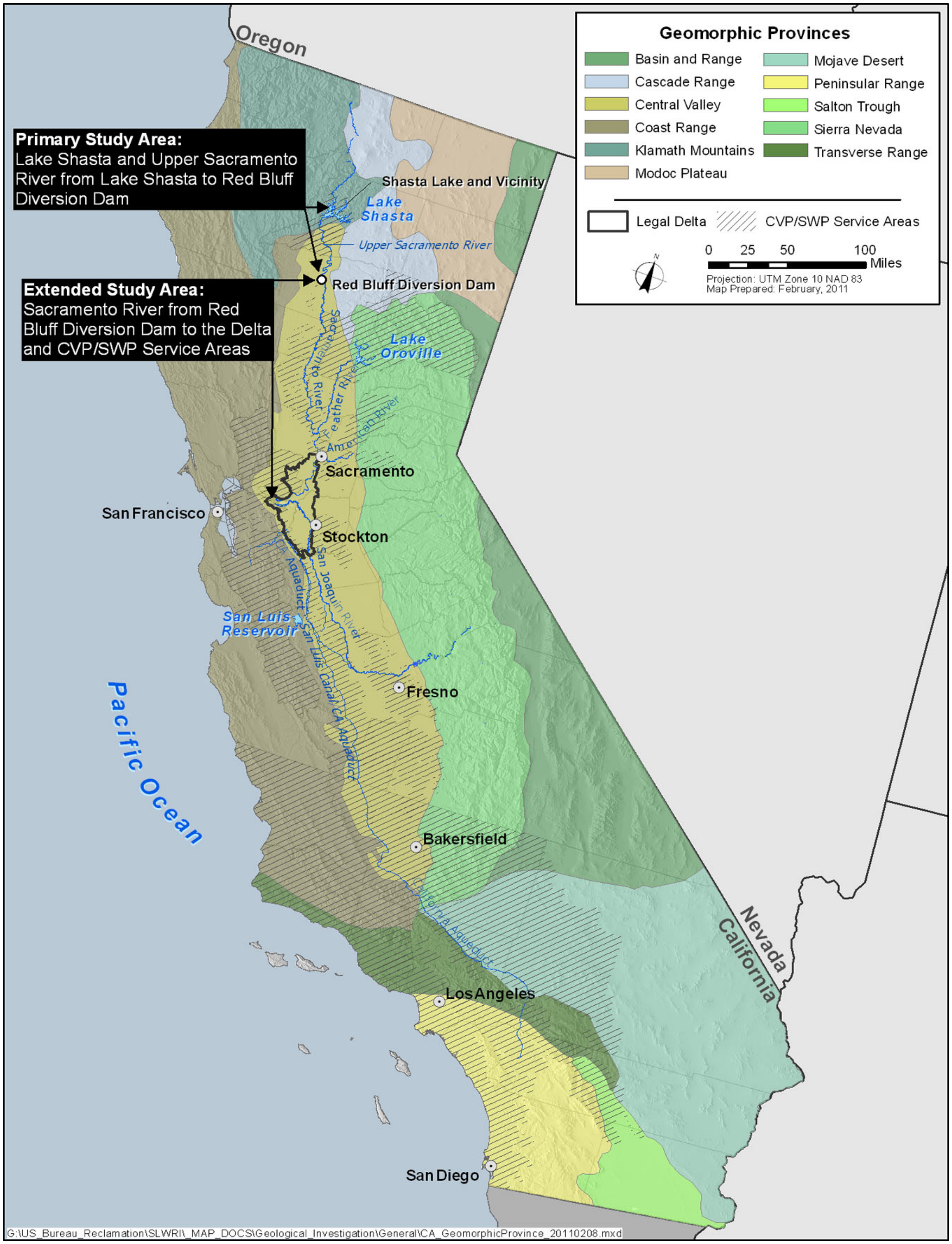


Figure 1-1. Shasta Lake and Vicinity Portion of the Primary Study Area



Source: Belitz et al. 2003

Figure 1-2. Geomorphic Provinces of California

Table 1-1. Geologic Timescale

Eon	Era	Period		Epoch
Phanerozoic	Cenozoic (65.5 million years ago to the Present)	Quaternary (1.8 million years ago to the Present)		Holocene (11,477 years ago to the Present)
				Pleistocene (1.8 million years ago to approximately 11,477 years ago)
		Tertiary (65.5 to 1.8 million years ago)		Pliocene (5.3 to 1.8 million years ago)
				Miocene (23.0 to 5.3 million years ago)
				Oligocene (33.9 to 23.0 million years ago)
				Eocene (55.8 to 33.9 million years ago)
				Paleocene (65.5 to 55.8 million years ago)
	Mesozoic (251.0 to 65.5 million years ago)	Cretaceous (145.5 to 65.5 million years ago)		Late or Upper
				Early or Lower
		Jurassic (199.6 to 145.5 million years ago)		Late or Upper
				Middle
				Early or Lower
		Triassic (251.0 to 199.6 million years ago)		Late or Upper
				Middle
				Early or Lower
	Paleozoic (542.0 to 251.0 million years ago)	Permian (299.0 to 251.0 million years ago)		Lopingian
				Guadalupian
				Cisuralian
		Carboniferous (359.2 to 299.0 million years ago)	Pennsylvanian (318.1 to 299.0 million years ago)	Late or Upper
				Middle
				Early or Lower
			Mississippian (359.2 to 318.1 million years ago)	Late or Upper
				Middle
				Early or Lower
		Devonian (416.0 to 359.2 million years ago)		Late or Upper
				Middle
				Early or Lower
		Silurian (443.7 to 416.0 million years ago)		Pridoli
				Ludlow
				Wenlock
				Llandovery
		Ordovician (488.3 to 443.7 million years ago)		Late or Upper
				Middle
				Early or Lower
		Cambrian (542.0 to 488.3 million years ago)		Late or Upper
				Middle
				Early or Lower
Proterozoic	Precambrian (approximately 4 billion years ago to 542.0 million years ago)			

Source: USGS 2007

Primary Study Area

The following sections describe the geology of the primary study area including Shasta Lake and vicinity and the upper Sacramento River (Shasta Dam to Red Bluff).

Shasta Lake and Vicinity The Shasta Lake and vicinity portion of the primary study area is illustrated in Figure 1-1. The drainages contributing to Shasta Lake cover a broad expanse of land with a widely diverse and complicated geology. Shasta Lake is situated geographically at the interface between the Central Valley, Klamath Mountains, and Modoc Plateau and Cascades geomorphic provinces.

The bedrock geology for the Shasta Lake and vicinity is shown in Figure 1-3. The mapping legend that accompanies Figure 1-3 is presented in Table 1-2. Shasta Lake itself and adjacent lands (i.e., Shasta Lake and vicinity) are underlain by rocks of the Klamath Mountains and, to a much more limited extent, the Modoc Plateau and Cascades geomorphic provinces. The regional topography is highly dissected, consisting predominantly of ridges and canyons with vertical relief ranging from the surface of Shasta Lake at 1,070 feet above msl to ridges and promontories more than 6,000 feet above msl. This diversity in topography is primarily a result of the structural and erosional characteristics of rock units in the Shasta Lake and vicinity area.

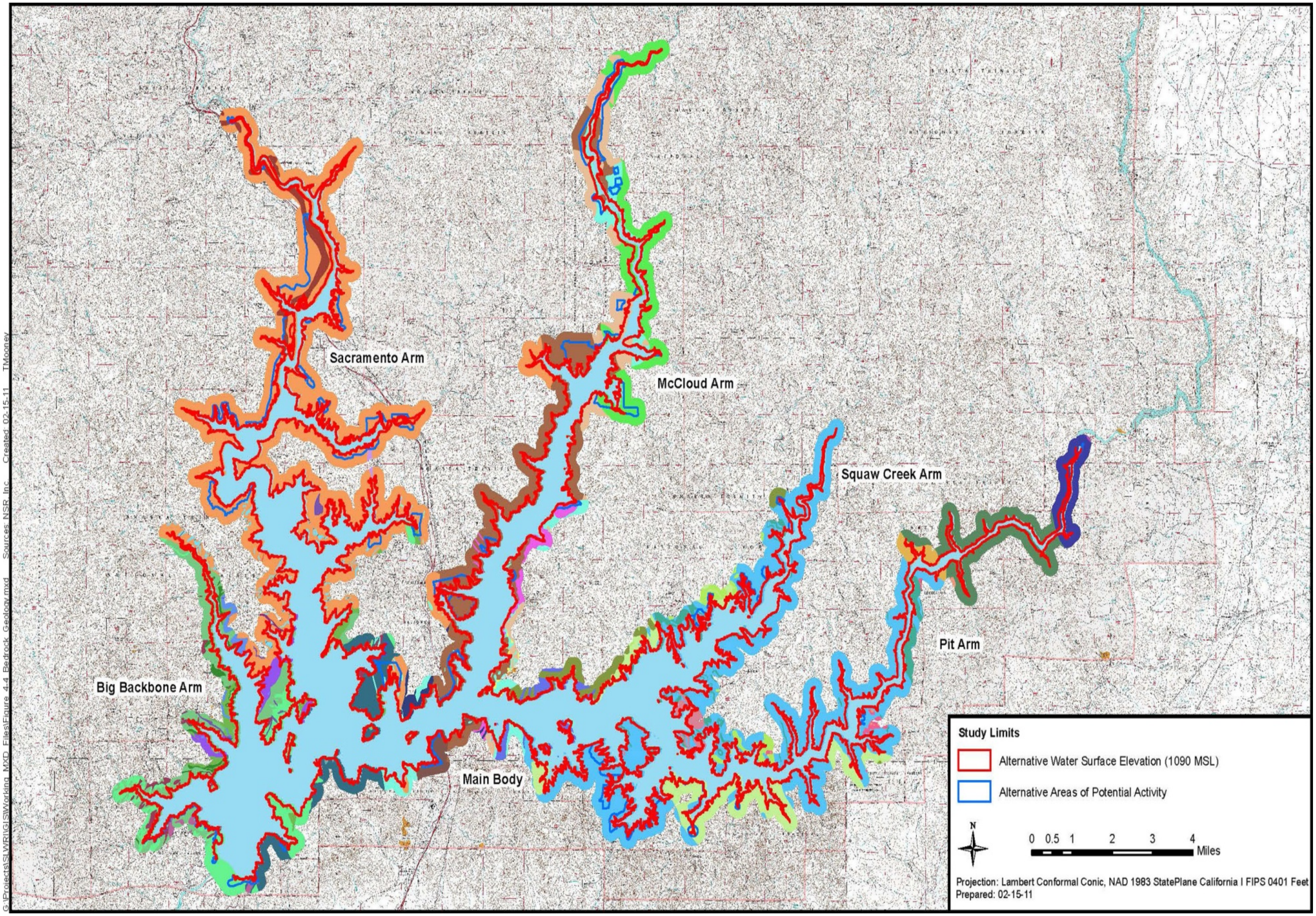


Figure 1-3. Bedrock Geology – Shasta Lake and Vicinity

Table 1-2. Key to Bedrock Geology Map Units – Shasta Lake and Vicinity

Map Unit, Formation, Description
Cb, Baird, meta-pyroclastic & keratophyre; & undiff.
Cbg, Bragdon, shale; graywacke; minor conglomerate
Cbgcp, Bragdon, chert-pebble & quartz conglomerate
Cbgp, Bragdon, pyroclastic; tuff; tuffaceous sediments
Cbgs, Bragdon, black siliceous shale
Cblss, Baird, skarn; lime silicate minerals; magnetite; locally
Cbmv, Baird, greenstone & greenstone breccia
Cbp, Baird, mafic pyroclastic rocks w/ minor tuffaceous mudsto
Db, Balaklala rhyolite, non-porphyritic & with small quartz phenocrysts (1
Dbc, Balaklala rhyolite, porphyritic with large quartz phenocrysts [>4 mm];
Dbp, Balaklala rhyolite, volcanic breccia; tuff breccia; volcanic conglomer
Dbt, Balaklala rhyolite, tuff & tuffaceous shale
Dc, Copley, greenstone; & undiff.
Dct, Copley, greenstone tuff & breccia; shaly tuff & shale
Dk, Kennett, siliceous shale & rhyolitic tuff; & undiff.
Dkls, Kennett, limestone
Dkt, Kennett, tuff; tuffaceous shale; shale
EHaev, , Andesite of Everitt Hill
Ja, Arvison, volcaniclastic & pyroclastic; & undiff.
Jp, Potem, argillite & tuffaceous sandstone; & undiff.
Pmbh, Bully Hill rhyolit, meta-andesite (quartz keratophyre); meta-dacite; p
Pmbhp, Bully Hill rhyolit, pyroclastic; tuff & tuff breccia
Pmd, , quartz diorite; albite - two pyroxene qd; mafic qd
Pmdk, Dekkas, mafic flows & tuff with minor mudstone & tuffaceou
Pmdkp, Dekkas, breccia; tuff; tuff breccia
Pmml, McCloud, limestone
Pmmls, McCloud, skarn; lime silicate minerals; magnetite; locally
Pmn, Nosoni, tuffaceous mudstone w/ lesser mafic flows; sandsto
Pmpr, Pit River stock, quartz diorite; granodiorite & plagiogranite; 261
Trh, Hosselkus Limeston, limestone; thin-bedded to massive; gray; fossilife
Trm, Modin, andesitic volcaniclastic & pyroclastic rocks; cong
Trp, Pit, shale; siltstone; metavolcanic; w/ limestone; & un
Trpmv, Pit, meta-andesite; meta-dacite; porphyritic & non-; ma
Trpp, Pit, pyroclastic; tuff & tuff breccia
Tt, Tuscan Formation, undivided: volcaniclastic; lahars; tuff; sandston
Tva, Western Cascades, andesite
Tvb, Western Cascades, basalt
di, , intermediate dikes
dia, , diabase dikes & small intrusive bodies
dpp, , plagioclase (+/- hornblende; quartz) porphyritic d
lake, , Shasta Lake; et al

Klamath Mountains Geomorphic Province The Klamath Mountains Geomorphic Province is located in northwestern California between the Coast Ranges on the west and the Cascade Range on the east. The Klamath Mountains consist of Paleozoic meta-sedimentary and meta-volcanic rocks and Mesozoic igneous rocks that make up individual mountain ranges extending to the north. The Klamath Mountains Geomorphic Province consists of four mountain belts: the eastern Klamath Mountain belt, central metamorphic belt, western Paleozoic and Triassic belt, and western Jurassic belt. Low-angle thrust faults occur between the belts and allow the eastern blocks to be pushed westward and upward. The central metamorphic belt consists of Paleozoic hornblende, mica schists, and ultramafic rocks. The western Paleozoic and Triassic belt, and the western Jurassic belt consist of slightly metamorphosed sedimentary and volcanic rocks.

A large portion of the Shasta Lake and vicinity area is underlain by rocks of the eastern Klamath Mountain belt. The strata of the eastern belt constitute a column 40,000 – 50,000 feet thick, and represent the time from the Ordovician period (about 490 years before present) to the Jurassic period (about 145 million years before present). The stratigraphic column of formations that compose the eastern Klamath Mountain belt, including a scale of geologic time, is shown in Table 1-3 (Hackel 1966). Important eastern belt rocks that underlie Shasta Lake and vicinity include metavolcanics of Devonian age (i.e., Copley Greenstone and Balaklala Rhyolite Formations), metasedimentary rocks of Mississippian age (i.e., Bragdon Formation), thin-bedded to massive sedimentary rocks of Permian age (i.e., McCloud Limestone Formation), and metasedimentary and metavolcanic rocks of Triassic age (i.e., Pit, Modin, and Bully Hill Rhyolite Formations) (Reclamation 2009). Intrusive igneous rocks (e.g., localized granitic bodies) make up fewer than 5 percent of the rocks in the area but are well represented on the Shasta Lake shoreline, particularly in the south-central area of the lake. Mesozoic intrusive dikes are scattered in the western portion of the map area.

Table 1-3. Stratigraphic Column of Formations of the Eastern Klamath Mountain Belt

Period/Age Before Present (million years)	Formation	Thickness (feet)	General Features
Jurassic 145-200 my	Potem Formation	1,000	Argillite and tuffaceous sandstones, with minor beds of conglomerate, pyroclastics, and limestone.
	Bagley Andesite	700	Andesitic flows and pyroclastics.
	Arvison Formation of Sanborn (1953)	5,090	Interbedded volcanic breccia, conglomerate, tuff, and minor andesitic lava flows.

Table 1-3. Stratigraphic Column of Formations of the Eastern Klamath Mountain Belt (contd.)

Period/Age Before Present (million years)	Formation	Thickness (feet)	General Features
Triassic 200-250 my	Modin Formation	5,500	Basal member of volcanic conglomerate, breccia, tuff, and porphyry, with limestone fragments from the Hosselkus formation.
	Brock Shale	400	Dark massive argillite interlayered with tuff or tuffaceous sandstone.
	Hosselkus Limestone	0-250	Thin-bedded to massive light-gray limestone.
	Pit Formation	2,000-4,400	Predominantly dark shale and siltstone, with abundant lenses of metadacite and quartz-keratophyre tuffs.
	Bully Hill Rhyolite	100-2,500	Lava flows and pyroclastic rocks, with subordinate hypabyssal intrusive bodies.
Permian 250-300 my	Dekkas Andesite	1,000-3,500	Chiefly fragmental lava and pyroclastic rocks, but includes mudstone and tuffaceous sandstone.
	Nosoni Formation	0-2,000	Mudstone and fine-grained tuff, with minor coarse mafic pyroclastic rocks and lava.
	McCloud Limestone	0-2,500	Thin-bedded to massive light-gray limestone, with local beds and nodules of chert.
Carboniferous 300-360 my	Baird Formation	3,000-5,000	Pyroclastic rocks, mudstone, and keratophyre flows in lower part; siliceous mudstone, with minor limestone, chert, and tuff in middle part; and greenstone, quartz, keratophyre, and mafic pyroclastic rocks and flow breccia in upper part.
	Bragdon Formation	6,000±	Interbedded shale and sandstone, with grit and chert-pebble conglomerate abundant in upper part.
Devonian 360-420 my	Kennett Formation	0-400	Dark, thin-bedded, siliceous mudstone and tuff.
	Balaklala Rhyolite	0-3,500	Light-colored quartz-keratophyre flows and pyroclastics.
	Copley Greenstone	3,700+	Keratophyric and spilitic pillow lavas and pyroclastic rocks.
Silurian 420-450 my	Gazelle Formation	2,400+	Siliceous graywackes, mudstone, chert-pebble conglomerate, tuff, and limestone.
Ordovician 450-490 my	Duzel Formation	1,250+	Thinly layered phyllitic greywacke, locally with radiolarian chert and limestone.

The McCloud Limestone is prominently exposed within the McCloud, Pit, Main Body, and Big Backbone arms of Shasta Lake. Within the lake footprint, the McCloud Arm has the largest exposure of this limestone, followed by the Pit, Main Body, and Big Backbone arms. Along the McCloud Arm, this limestone crops out on the eastern shore from the mouth at the main body of the lake to Hirz Bay. Above Hirz Bay, it is intermittently exposed on both sides of the McCloud Arm. Along the Pit Arm near the mouth of Brock Creek, the McCloud Limestone is exposed along the north and southern banks. The McCloud Limestone is exposed near the southern shore of Allie Cove in the eastern portion of the Main Body of the lake. Along the Big Backbone Arm, the McCloud Limestone is exposed near the eastern shore between the outlets of Shoemaker and Limerock creeks. Outside the Shasta Lake footprint, an outcrop of the McCloud Limestone is exposed along the McCloud River approximately 10 miles upstream from the mouth into the McCloud Arm. The McCloud Limestone is also exposed on the north side of Bohemotash Mountain, which is approximately 2 miles from the mouth of Big Backbone Creek at the Big Backbone Arm.

“Skarn” is a geologic term that refers to metamorphic rocks formed in the contact zone of magmatic intrusions (e.g., granite) with carbonate-rich rocks (e.g., limestone.) Skarn deposits are rich in lime-silicate minerals, and locally contain magnetite. Permian-aged skarn deposits are present within the McCloud Arm. The deposits are located near the mouths of Marble and Potter creeks and on the peninsula at the eastern margin of the inlet of the McCloud Arm. The skarn deposits occur adjacent to the McCloud Limestone at the mouths of Marble and Potter creeks, but the McCloud Limestone is absent near skarn deposits on the peninsula.

A small area of the fossiliferous Cretaceous Chico Formation, consisting of Great Valley marine sedimentary rocks, occurs near Jones Valley Creek, a tributary to the Pit Arm. Although this rock unit occurs in the immediate vicinity, it is not exposed along the shoreline of the lake and falls outside the Shasta Lake and vicinity area. Some outcrops of McCloud Limestone, especially in the vicinity of the McCloud River Bridge, are also fossiliferous.

Modoc Plateau and Cascades Geomorphic Provinces The Cascade Range and Modoc Plateau together cover approximately 13,000 square miles in the northeast corner of California. The Cascade Range and Modoc Plateau (collectively the Modoc Plateau and Cascades Geomorphic Province) are very similar geologically and consist of young volcanic rocks, that are of Miocene to Pleistocene age. Included in this province are two composite volcanoes, Mount Shasta and Lassen Peak, and the Medicine Lake Highlands, a broad shield volcano.

The Cascade volcanics have been divided into the Western Cascade series and the High Cascade series. The Western Cascade series rocks consists of Miocene-aged basalts, andesites, and dacite flows interlayered with rocks of explosive origin, including rhyolite tuff, volcanic breccia, and agglomerate. This series is exposed at the surface in a belt 15 miles wide and 50 miles long from the Oregon border to the town of Mount Shasta. After a short period of uplift and erosion that extended into the Pliocene, volcanism resumed creating the High Cascade volcanic series. The High Cascade series forms a belt 40 miles wide and 150 miles long just east of the Western Cascade series rocks. Early High Cascade rocks formed from very fluid basalt and andesite that extruded from fissures to form low shield volcanoes. Later eruptions during the Pleistocene contained more silica, causing more violent eruptions. Large composite cones like Mount Shasta and Lassen Peak had their origins during the Pleistocene (Norris and Webb 1990).

The Modoc Plateau consists of a high plain of irregular volcanic rocks of basaltic origin. The numerous shield volcanoes and extensive faulting on the plateau give the area more relief than otherwise may be expected for a plateau. The Modoc Plateau averages 4,500 feet in elevation and is considered a small part of the Columbia Plateau, which covers extensive areas of Oregon, Washington, and Idaho.

Volcanic rocks of the Modoc Plateau and Cascades Geomorphic Province are present adjacent to the eastern and northeastern boundaries of the Shasta Lake and vicinity area. In the vicinity of Shasta Lake they occur near the Pit Arm and along the upper Sacramento Arm. These rocks are generally younger than 4 million years old. Volcaniclastic rocks, mudflows, and tuffs of the Tuscan Formation occur in the Pit River area, and localized volcanic deposits occur in isolated locations.

The areal extent of bedrock types within the Shasta Lake and Vicinity area is presented in Table 1-4 for the portion of the area between 1,070 feet and 1,090 feet above msl (i.e., Impoundment Area), and in Table 1-5 for the portion potentially disturbed by construction activities (i.e., Relocation Areas.)

Table 1-4. Areal Extent of Bedrock Types – Shasta Lake and Vicinity (Impoundment Area)

Map Unit	Formation	Bedrock Types	Acres	% of Total Impoundment Area
Cb	Baird	Meta-pyroclastic and keratophyre	145.3	5.82%
Cbg	Bragdon	Shale; graywacke; minor conglomerate	468.9	18.77%
Cbgcp	Bragdon	Chert-pebble and quartz conglomerate	3.3	0.13%
Cbgs	Bragdon	Black siliceous shale	0.0	0.00%
Cblss	Baird	Skarn; lime silicate minerals	1.2	0.05%
Cbmv	Baird	Greenstone and greenstone breccia	6.7	0.27%
Cbp	Baird	Mafic pyroclastic rocks	4.8	0.19%
Db	Balaklala rhyolite	Non-porphyritic and with small quartz phenocrysts	52.8	2.11%
Dbc	Balaklala rhyolite	Porphyritic with large quartz phenocrysts	3.3	0.13%
Dbp	Balaklala rhyolite	Volcanic breccia; tuff breccia; volcanic conglomer	12.9	0.52%
Dbt	Balaklala rhyolite	Tuff and tuffaceous shale	5.9	0.24%
Dc	Copley	Greenstone and undiff.	48.9	1.96%
Dct	Copley	Greenstone tuff and breccia	33.4	1.34%

Table 1-4. Areal Extent of Bedrock Types – Shasta Lake and Vicinity (Impoundment Area) (contd.)

Map Unit	Formation	Bedrock Types	Acres	% of Total Impoundment Area
di		Intermediate dikes	0.6	0.02%
dia		Diabase dikes	0.2	0.01%
Dk	Kennett	Siliceous shale and rhyolitic tuff	20.0	0.80%
Dkls	Kennett	Limestone	1.9	0.07%
Dkt	Kennett	Tuff; tuffaceous shale; shale	11.2	0.45%
dpp		Plagioclase	0.7	0.03%
Ehaev		Andesite	17.9	0.72%
Ja	Arvison	Volcaniclastic and pyroclastic	9.6	0.38%
lake	Shasta Lake		924.0	36.99%
Pmbh	Bully Hill rhyolite	Meta-andesite	84.6	3.39%
Pmbhp	Bully Hill rhyolite	Pyroclastic; tuff and tuff breccia	11.0	0.44%
Pmd		Quartz diorite	47.5	1.90%
Pmdk	Dekkas	Mafic flows and tuff	18.9	0.76%
Pmdkp	Dekkas	Breccia; tuff; tuff breccia	16.7	0.67%
Pmml	McCloud	Limestone	26.7	1.07%
Pmmls	McCloud	Skarn; lime silicate minerals; magnetite	2.2	0.09%
Pmn	Nosoni	Tuffaceous mudstone	66.4	2.66%
Pmpr	Pit River Stock	Quartz diorite; granodiorite	11.2	0.45%
Trh	Hosselkus Limestone	Limestone; thin-bedded to massive; gray; fossilife	7.5	0.30%
Trm	Modin	Andesitic volcaniclastic and pyroclastic rocks	27.9	1.12%
Trp	Pit	Shale; siltstone; metavolcanic; wi limestone	374.8	15.00%
Trpmv	Pit	Meta-andesite; meta-dacite	12.0	0.48%
Trpp	Pit	Pyroclastic; tuff and tuff breccia	16.6	0.66%
Tva	Western Cascades	Andesite	0.5	0.02%

Table 1-5. Areal Extent of Bedrock Types – Shasta Lake and Vicinity (Relocation Areas)

Map Unit	Formation	Bedrock Types	Acres	% of Total Relocation Area
Cb	Baird	Meta-pyroclastic and keratophyre	530.8	15.90%
Cbg	Bragdon	Shale; graywacke; minor conglomerate	1088.4	32.59%
Cbgcp	Bragdon	Chert-pebble and quartz conglomerate	0.6	0.02%
Cbmv	Baird	Greenstone and greenstone breccia	25.6	0.77%
Db	Balaklala rhyolite	Non-porphyritic and with small quartz phenocrysts	9.8	0.29%
Dbc	Balaklala rhyolite	Porphyritic with large quartz phenocrysts	7.8	0.23%
Dbp	Balaklala rhyolite	Volcanic breccia; tuff breccia; volcanic conglomer	3.9	0.12%
Dbt	Balaklala rhyolite	Tuff and tuffaceous shale	1.1	0.03%
Dc	Copley	Greenstone and undiff.	61.5	1.84%
Dct	Copley	Greenstone tuff and breccia	84.9	2.54%
Dk	Kennett	Siliceous shale and rhyolitic tuff	10.3	0.31%
Dkls	Kennett	Limestone	0.4	0.01%
Dkt	Kennett	Tuff; tuffaceous shale; shale	0.0	0.00%
Ehaev		Andesite	261.4	7.83%
Ja	Arvison	Volcaniclastic and pyroclastic	0.7	0.02%
lake	Shasta Lake		242.0	7.25%
Pmbh	Bully Hill rhyolite	Meta-andesite	53.0	1.59%
Pmbhp	Bully Hill rhyolite	Pyroclastic; tuff and tuff breccia	7.5	0.22%
Pmd		Quartz diorite	100.5	3.01%
Pmdk	Dekkas	Mafic flows and tuff	8.8	0.26%
Pmdkp	Dekkas	Breccia; tuff; tuff breccia	18.5	0.55%
Pmml	McCloud	Limestone	174.9	5.24%
Pmn	Nosoni	Tuffaceous mudstone	182.5	5.46%
Pmpr	Pit River Stock	Quartz diorite; granodiorite	42.8	1.28%
Trp	Pit	Shale; siltstone; metavolcanic; wi limestone	408.5	12.23%
Trpp	Pit	Pyroclastic; tuff and tuff breccia	11.5	0.34%
Tva	Western Cascades	Andesite	2.0	0.06%

Cave and Karst Resources

Karst geomorphology is named after the Karst region in Slovenia, where limestone has been geologically carved into world-famous caves and other karst landforms. Caves and karst landforms are found along the Big Backbone Arm, the McCloud Arm, and the Pit Arm (Brock Creek).

Nine caves in the National Recreational Area (NRA) adjacent to Shasta Lake—Dekkas Rock Staircase Cave, Lake Level Cave, Clay Doe Cave, Jolly Time Cave, Blanchet Cave, two caves known as the McCloud Bridge Caves, and two caves known as the Town Mountain Caves—could be periodically inundated under the five comprehensive plans (USFS 2012). The first three of these caves are registered under the Federal Cave Resource Protection Act of 1988. Dekkas Rock Staircase and the two McCloud Bridge caves are already periodically inundated under the current elevation of the dam. Field investigations performed to date have not identified any other caves that would be affected by the raising of Shasta Dam.

Upper Sacramento River (Shasta Dam to Red Bluff) Shasta Dam and Reservoir are located on the northern edge of California's Central Valley, which is almost completely enclosed by mountains, and has only one outlet, through San Francisco Bay, to the Pacific Ocean. The valley is nearly 500 miles long and averages 120 miles wide. The Central Valley is drained by the Sacramento River in the northern portion and the San Joaquin River and Tulare Lake tributaries in the southern portion.

Downstream from the dam, the Sacramento River travels south to the Delta, picking up additional flows from numerous tributaries, including Cottonwood Creek, Battle Creek, Feather, Yuba, and American Rivers. The Sacramento River basin covers approximately 27,000 square miles and is about 240 miles long and up to 150 miles wide. Ground surface elevations measure approximately 1,070 feet at the maximum water surface elevation at Shasta Lake, decreasing toward the relatively flat southern portion of the Sacramento River basin.

The portion of the primary study area along the Sacramento River downstream to the RBPP encompasses portions of the Cascade Range, Klamath Mountains, and Central Valley Geomorphic Provinces (see Figure 1-2). Descriptions of the Cascade Range and Klamath Mountains geomorphic provinces are provided in the Shasta Lake and vicinity discussion above.

Central Valley Geomorphic Province The Central Valley Geomorphic Province is a large, asymmetrical, northwest-trending, structural trough formed between the uplands of the California Coast Ranges to the west and the Sierra Nevada to the east, and is approximately 400 miles long and 50 miles wide (Page 1985). The Coast Ranges to the west are made up of pre-Tertiary and Tertiary semiconsolidated to consolidated marine sedimentary rocks. The Coast Range sediments are folded and faulted and extend eastward beneath most of the Central Valley. The Sierra Nevada to the east side of the valley is composed of pre-Tertiary igneous and metamorphic rocks. Before the rise of the Coast Range, approximately 25,000 feet of pre-Tertiary marine sediments were deposited in the sea. The marine deposits continued to accumulate in the Sacramento Valley until the Miocene Epoch, and portions of the San Joaquin Valley until late Pliocene, when the sea receded from the valley. The continental alluvial deposits from the Coast Range and the Sierra Nevada began to collect in the newly formed valley. This trough has been filled with a tremendously thick sequence of sediments ranging in age from Jurassic to Recent that extends approximately 6 vertical miles in the San Joaquin Valley and 10 vertical miles in the Sacramento Valley (Page 1985).

Along the western side of the Sacramento Valley, rocks of the Central Valley Geomorphic Province include Upper Jurassic to Cretaceous marine sedimentary rocks of the Great Valley Sequence; fluvial deposits of the Tertiary Tehama Formation; Quaternary Red Bluff, Riverbank, and Modesto formations; and Recent alluvium.

The Great Valley Sequence was formed from sediments deposited within a submarine fan along the continental edge. The sediment sources were the Klamath Mountains and Sierra Nevada to the north and east, and include mudstones, sandstones, and conglomerates.

The mudstones of the Great Valley Sequence are typically dark gray to black. Generally, the mudstones are thinly laminated and have closely spaced and pervasive joints. When fresh, the mudstones are hard, but exposed areas weather and slake readily.

Fresh sandstones encountered in the Great Valley Sequence are typically light green to gray; weathered sandstones are typically tan to brown. They are considered to be graywackes in some places because of the percentage of fine-grained interstitial material. Sandstone beds range from thinly laminated to massive. In many places, the sandstones are layered with beds of conglomerates, siltstones, and mudstones. Massive sandstones are indurated, have widely spaced joints, and form the backbone of most of the ridges.

Conglomerates found are closely associated with the massive sandstones and consist of lenticular and discontinuous beds varying in thickness from a few feet to more than 100 feet. Conglomerate clasts range in size from pebbles to boulders and comprise primarily chert, volcanic rocks, granitic rocks, and sandstones set in a matrix of cemented sand and clay. The conglomerates are similar to the sandstones in hardness and jointing.

Tertiary and Quaternary fluvial sedimentary deposits unconformably overlie the Great Valley Sequence. The Pliocene Tehama Formation is the oldest. It is derived from erosion of the Coast Ranges and Klamath Mountains and consists of pale green to tan semiconsolidated silt, clay, sand, and gravel. Along the western margin of the valley, the Tehama Formation is generally thin, discontinuous, and deeply weathered.

The Quaternary Red Bluff Formation comprises reddish poorly sorted gravel with thin interbeds of reddish clay. The Red Bluff Formation is a broad erosional surface, or pediment, of low relief formed on the Tehama Formation between 0.45 and 1.0 million years ago. Thickness varies to about 30 feet. The pediment is an excellent datum to assess Pleistocene deformation because of its original widespread occurrence and low relief.

Alluvium is defined as loose sedimentary deposit of clay, silt, sand, gravel, and boulders. They may be deposits originating from landslides, colluvium, stream channel deposits, and floodplain deposits. Landslides occur along the project area but are generally small, shallow debris slides or debris flows.

Stream channel deposits generally consist of unconsolidated sand and gravel, with minor amounts of silt and clay. Floodplain deposits are finer grained and consist almost entirely of silt and clay (DWR 2003).

Stream terraces form flat benches adjacent to and above the active stream channel. Up to nine different stream terrace levels have been identified in the Great Valley. Terrace deposits consist of 2 to 10 feet of clay, silt, and sand overlying a basal layer of coarser alluvium containing sand, gravel, cobbles, and boulders. Four terrace levels have been given formational names by the U.S. Geological Survey (USGS) (Helley and Harwood 1985) – the Upper Modesto, Lower Modesto, Upper Riverbank, and Lower Riverbank – and they range in age from 10,000 to several hundred thousand years old.

Extended Study Area

The extended study area includes the Sacramento River Basin downstream from the RBPP to the Delta, the Delta itself, the San Joaquin River Basin to the Delta, portions of the American River basin, and the CVP and SWP service areas. Geology in the extended study area is described below.

Lower Sacramento River and Delta The segment of the extended study area along the lower Sacramento River and the Delta encompasses the Central Valley Geomorphic Province. The Central Valley geomorphic province is described above in the description of geology of the upper Sacramento River (Shasta Dam to Red Bluff). The Central Valley geomorphic province has a long, stable eastern shelf that is supported by metamorphic and igneous rocks of the west-dipping Sierran slope. The basement rocks of the western edge of the structural trough comprise Jurassic metamorphic, ultramafic, and igneous rocks of the Franciscan Formation (Hackel 1966). The northwest-trending axis of the geosyncline is closer to the west side of the valley; therefore, the regional dip of the formations on the east side is less than that of the formations on the west side. This structural trough has been filled with sediments derived from both marine and continental sources. The thickness of the valley fill ranges from thin sections along the valley edges to sections greater than 40,000 feet in the central part of the valley. The marine deposits were formed in offshore shallow ocean shelf and basin environments. Continental sediments were derived from mountain ranges surrounding the valley, and were deposited in lacustrine, fluvial, and alluvial environments (Norris and Webb 1990).

The Delta is a broad depression in the Franciscan bedrock that resulted from an east-west expansion of the San Andreas and Hayward fault systems, filled by sediments deposited over many millions of years via the Sacramento and San Joaquin rivers and other tributary rivers and streams.

CVP/SWP Service Areas The extended study area, which contains the CVP and SWP service areas, encompasses much of the Sacramento and San Joaquin valleys and substantial portions of the Bay Area and Southern California. Thus, the extended study area encompasses portions of all of the geomorphic provinces of California, except the Basin and Range and Colorado Desert. The geomorphic provinces encompassed in the CVP and SWP service areas include the Central Valley, Sierra Nevada, Coast Ranges, Cascade Range, Peninsular Ranges, Transverse Ranges, Mojave Desert, Modoc Plateau, and Klamath Mountains. Descriptions of the Central Valley, Cascade Range, Modoc Plateau, and Klamath Mountains geomorphic provinces are provided above.

Sierra Nevada Geomorphic Province The Sierra Nevada extends approximately 400 miles long and is bordered to the north by the Cascade Range. The Sierra Nevada geomorphic province is a tilted fault block that consists of rocks early Paleozoic (Cambrian to Ordovician) to more recent Phanerozoic (Holocene) in age. The Sierra Nevada contains a portion of the CVP and SWP service areas within the western San Joaquin Valley.

Coast Ranges Geomorphic Province The Coast Ranges consist of ranges and valleys that trend northwest, subparallel to the San Andreas Fault, and are composed of Mesozoic and Cenozoic sedimentary strata. The Bay Area is located within the Coast Ranges and occupies a structural trough that formed during the late Cenozoic when it was part of a great drainage basin of the ancestral San Joaquin, Sacramento, and Coyote rivers. The bay was formed between 10,000 and 25,000 years ago, when the polar ice caps melted at the end of the fourth glacial period. Sea level rose in response to the melting of the ice caps. As the ocean rose, it flooded river valleys inland of the Golden Gate Bridge, forming San Francisco Bay, San Pablo Bay, and Suisun Bay.

The Coast Ranges also contain a portion of the CVP and SWP service areas within the eastern San Joaquin Valley and a portion of the south-of-Delta CVP and SWP service areas.

Peninsular Ranges Geomorphic Province The Peninsular Ranges consist of a series of ranges that are separated by northwest trending valleys, subparallel to faults that branch from the San Andreas Fault, and are bound on the east by the Colorado Desert. The Peninsular Ranges contains a portion of the southern section of the south-of-Delta CVP and SWP service areas.

Transverse Ranges Geomorphic Province The Transverse Ranges extend across a series of steep mountain ranges and valley and trend from east to west. The Transverse Ranges encompass a relatively small area within California, but they contain the greatest number of rock types and structures of all the geomorphic provinces in California, from the Proterozoic to the Phanerozoic (Norris and Webb 1990). The Transverse Ranges contains a portion of the southern section of the south-of-Delta CVP and SWP service areas.

Mojave Desert Geomorphic Province The Mojave Desert Geomorphic Province consists of isolated mountain ranges separated by desert plains. The topography of the Mojave Desert is controlled by two faults, the San Andreas Fault, trending northwest to southeast and the Garlock Fault, trending east to west (Wagner 2002). The Mojave Desert Geomorphic Province contains Proterozic, Paleozoic, and lower Mesozoic rocks with scarce quantities of Triassic and Jurassic marine sediments (Norris and Web 1990). The Mojave Desert contains a portion of the southern section of the south-of-Delta CVP and SWP service areas.

1.1.2 Geologic Hazards

Geologic hazards are described below for both the primary and extended study areas.

Primary Study Area

The following sections describe geologic hazards of the primary study area, including Shasta Lake and vicinity and the upper Sacramento River (Shasta Dam to Red Bluff).

Shasta Lake and Vicinity Six types of geologic hazards have potential to occur within the Shasta Lake and vicinity project area: seismic hazards, volcanic eruptions and associated hazards, mudflows, snow avalanches, slope instability, and seiches.

Seismic Hazards Seismic hazards consist of the effects of ground shaking and surface rupture along and around the trace of an active fault. Ground shaking is the most hazardous effect of earthquakes because it is the most widespread and accompanies all earthquakes. Ground shaking can range from high to low intensity and is often responsible for structural failure leading to the largest loss of life and property damage during an earthquake. The Modified Mercalli intensity ratings reflect the relationship between earthquake magnitudes and shaking intensity. Higher magnitude earthquakes typically produce higher shaking intensities over wider areas, which may result in greater damage.

Surface rupture occurs when an earthquake results in ground rupture, causing horizontal and/or vertical displacement. Surface rupture typically is narrow in rock and wider in saturated soils, and also typically tends to occur along previous fault lines.

An active fault is defined by the Alquist-Priolo Earthquake Fault Zoning Act as a fault that has caused surface rupture within the last 11,000 years. The nearest active fault to the southern portion of the Shasta Lake and vicinity study area is the Battle Creek Fault Zone located approximately 27 miles south of the Shasta Dam (CDMG 2006). The maximum credible earthquake for the southern portion of the Shasta Lake and vicinity area has a moment magnitude of 7.3. A maximum peak ground acceleration (PGA) of 0.101 g[1] was calculated for the southern portion of the Shasta Lake and vicinity area based on an earthquake moment magnitude of 6.5 from the Battle Creek Fault Zone. The Northeastern California Fault system, located approximately 28 miles south of Shasta Dam, may be capable of causing the highest ground shaking at the site. A maximum PGA of 0.126 g was calculated for the Shasta Dam location.

According to the California Geological Survey's Alquist-Priolo Act Active Fault Maps, the nearest active fault north of the Shasta Lake and vicinity area is the Hat Creek – Mayfield– McArthur Fault Zone, located about 50 miles to the northeast of Shasta Dam (Jennings 1975). This fault zone is composed of numerous parallel north-northwest– trending normal faults. According to the Alquist-Priolo Act maps, the Hat Creek– Mayfield– McArthur Fault is capable of generating magnitude 7.0 earthquakes with a relatively long return period of 750 years (Petersen et al. 1996).

Other earthquake fault zones within or near the Shasta Lake and vicinity area include the following:

- Pittville Fault located in portions of the Day Bench
- Rocky Ledge Fault located north of Burney in Long Valley and east of Johnson Park

Northeast of the Shasta Lake and vicinity area, portions of Shasta and Siskiyou counties include the area between Lassen Peak and the Medicine Lake Highlands. This area is cut by a series of active normal faults that are part of the Sierra Nevada– Great Basin dextral shear zone (Shasta County 2004). These faults are capable of affecting the upper watersheds northeast of the Sacramento Valley. These faults include the previously mentioned Hat Creek– Mayfield– McArthur Fault Zone, the Gillem-Big Crack Faults near the California-Oregon border southeast of Lower Klamath Lake, and the Cedar Mountain Fault southwest of Lower Klamath Lake. The faults in this zone are capable of earthquakes up to magnitude 7.0. Farther northeast, the Likely Fault is judged capable of a magnitude 6.9 earthquake. In the northeast corner of the state, the Surprise Fault is capable of a magnitude 7.0 earthquake.

Seismic activity has been reported in the area of Shasta Dam and Shasta Lake, and has typically been in the 5.0 magnitude or lower range. The nearest seismic activity to Shasta Dam and Shasta Lake was a magnitude 5.2 earthquake that occurred 3 miles northwest of Redding, near Keswick Dam, in 1998 (Petersen 1999).

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[1] Peak ground acceleration is expressed in units of "g", the acceleration caused by Earth's gravity. Thus, 1g = 9.81meters per second squared (i.e. m/s^2)

Volcanic Eruptions and Associated Hazards Volcanic hazards include potential eruptions, and their products and associated hazards. In the Shasta Lake and Vicinity area these include lava flows, pyroclastic flows, domes, tephra, and mudflows and floods triggered by eruptions. Three active centers of volcanic activity, all associated with the Modoc Plateau and Cascades Geomorphic Province, occur near enough to the Shasta Lake and vicinity area to merit discussion: the Medicine Lake Highlands, Lassen Peak, and Mount Shasta.

The Medicine Lake Highlands is located approximately 65 air miles northeast of Shasta Lake and includes a broad shield volcano that has a large caldera at its summit and more than 100 smaller lava cones and cinder cones on its flanks. The volcano developed over a period of 1 million years, mainly through lava flows. The most recent activity was approximately 500 years ago, when a large tephra eruption was followed by an extrusion of obsidian. Volcanic activity is likely to persist in the future (U.S. Forest Service (USFS) 1994), specifically as local lava flows and tephra eruptions.

Lassen Peak lies 50 miles southeast of Shasta Lake. Lassen Peak is a cluster of dacitic domes and vents that have formed over the past 250,000 years. The most recent eruption occurred in 1914. That eruption began as a tephra eruption with steam blasts, and climaxed with a lateral blast, hot avalanches, and mudflows. Most ash from the 1914 eruption was carried to the east of the volcano.

The most prominent, active volcanic feature in the vicinity of Shasta Lake is Mount Shasta, which is located approximately 45 miles north of Shasta Lake. Mount Shasta has erupted at least once per 800 years during the last 10,000 years, and about once per 600 years during the last 4,500 years. Mount Shasta last erupted in 1786. Eruptions during the last 10,000 years produced lava flows and domes on and around the flanks of Mount Shasta. Pyroclastic flows extended up to 12 miles from the summit. Most of these eruptions also produced mudflows, many of which reached tens of miles from Mount Shasta.

Eruptions of Mount Shasta could endanger the communities of Weed, Mount Shasta, McCloud, and Dunsmuir. Such eruptions will most likely produce deposits of lithic ash, lava flows, domes, and pyroclastic flows that may affect low- and flat-lying ground almost anywhere within 12 miles of the summit. However, on the basis of its past behavior, Mount Shasta is not likely to erupt large volumes of pumiceous ash (tephra) in the future. Areas subject to the greatest risk from air-fall tephra are located mainly east and within about 30 miles of the summit (Miller 1980).

Floods commonly are produced by melting of snow and ice during eruptions of ice-clad volcanoes like Mount Shasta, or by heavy rains which may accompany eruptions. By incorporating river water as they move down valleys, mudflows may grade into slurry floods carrying unusually large amounts of rock debris. Eruption-caused floods can occur suddenly and can be of large volume. If floods caused by an eruption occur when rivers are already high, floods far larger than normal can result. Streams and valley floors around Mount Shasta could be affected by such floods as far downstream as Shasta Lake. The danger from floods caused by eruptions is similar to that from floods having other origins, but floods caused by eruptions may be more damaging because of a higher content of sediment which would increase the bulk specific gravity of the fluid (Miller 1980).

Mudflows Small mudflows, not caused by eruptions, are common at Mount Shasta. Relatively small but frequent mudflows have been produced historically (1924, 1926, 1931, and 1977) by melting of glaciers on Mount Shasta during warm summer months. Mudflows that occurred during the summer of 1924 entered the McCloud River and subsequently flowed into the Sacramento River (Miller 1980).

Snow Avalanches Avalanche hazards near the Shasta Lake and Vicinity area typically occur in steep, high-elevation terrane. These areas are generally above the tree line or in sparsely vegetated areas. Significant avalanche areas are limited to locations on the upper slopes outside of the Shasta Lake and vicinity area.

Slope Instability (Mass Wasting) Slope instability hazards occur in areas of active and relict mass wasting features (e.g., active and relict landslides, debris flows, inner gorge landscape positions, and complexes of these features.) Slope instability hazards occur throughout the Shasta Lake and vicinity area, and are most common in areas of steep topography. Locations in the Shasta Lake and vicinity area of mapped slope instability hazards are shown in Figure 1-4.

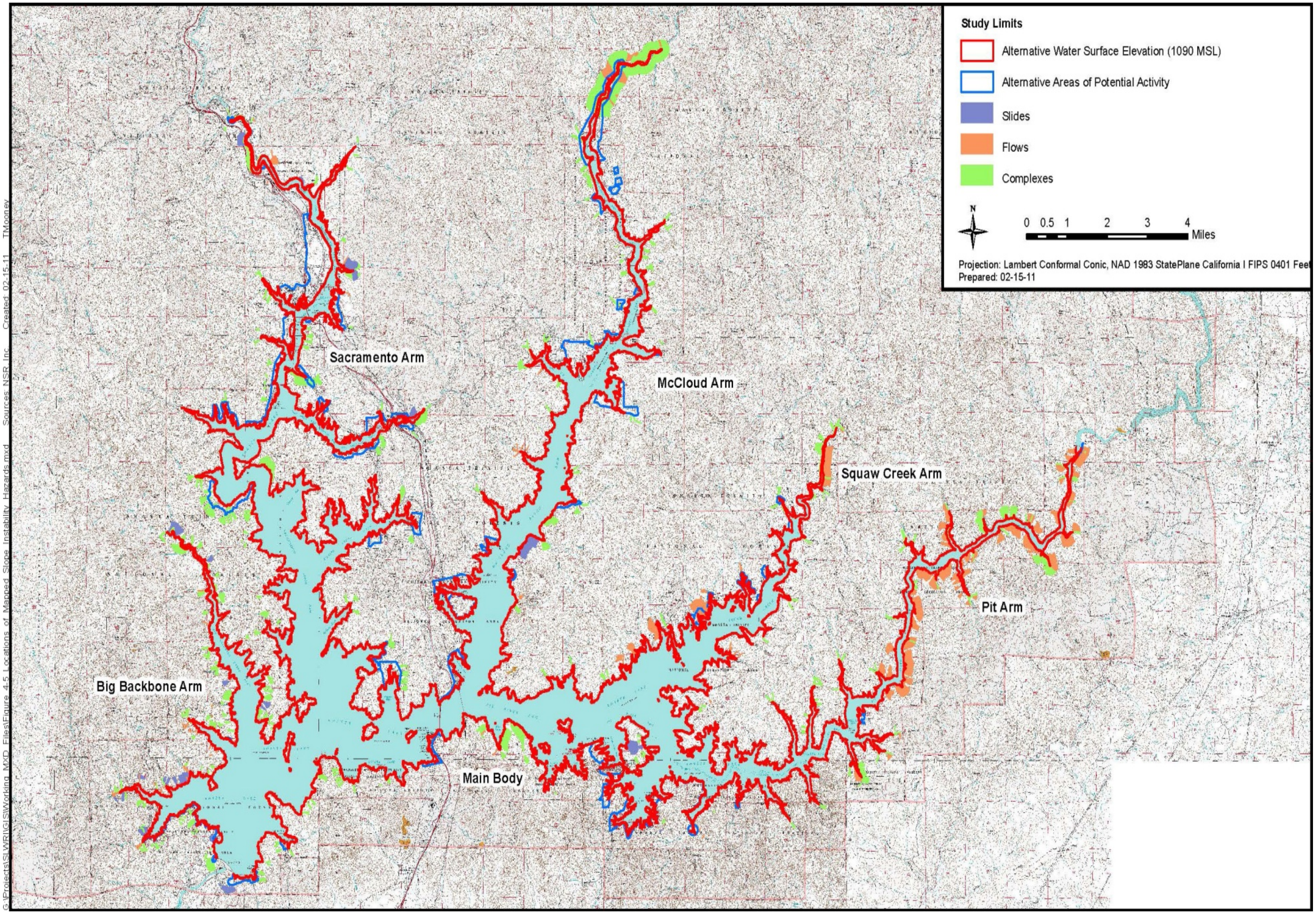


Figure 1-4. Locations of Mapped Slope Instability Hazards – Shasta Lake and Vicinity

The terrane underlying the Shasta Lake and vicinity area and the surrounding region has been influenced by a combination of tectonic uplift, mass wasting, and fluvial and surface erosion processes. The influence of these processes is ongoing, with evidence of ancient and more recent mass wasting features over the entire area, consisting of debris slides, torrents, and flows, with lesser amounts of rotational/translational landslides. The extent or distribution of mass wasting features across the region is believed not to have changed appreciably as a result of land use activities following Anglo-American settlement (USFS 1998).

Much of the topography in the general vicinity of the Shasta Lake and vicinity area is steep, with concave swales; therefore, landslides are relatively common, ranging from small mudflows and slumps to large debris slides, debris flows, and inner gorge landslides. Small shallow debris slides associated with localized alluvial/colluvial rock units also occur along the shoreline of Shasta Lake. Rock slides caused by mining activities have also occurred on the slopes surrounding Shasta Lake.

The areal extent of mapped slope instability hazards in the Shasta Lake and Vicinity area is presented in Table 1-6 for the portion of the area between 1,070 feet and 1,090 feet above msl (Impoundment Area); and in Table 1-7 for the portion potentially disturbed by construction activities under the action alternatives (Relocation Areas). About 173 acres (7 percent) of the Impoundment Area is occupied by features that are potentially unstable. Potentially unstable features occupy about 232 acres (7 percent) of the Relocation Area. Most of the mapped slope instability hazards are debris flows.

Table 1-6. Areal Extent of Mapped Slope Instability Hazards – Shasta Lake and Vicinity (Impoundment Area)

Map Unit	Formation	Acres	% of Impoundment Area Acreage)
1050	Slides	9.5375	0.38%
1100	Flows	66.6091	2.67%
1200	Complexes	97.1695	3.89%

Table 1-7. Areal Extent of Mapped Slope Instability Hazards – Shasta Lake and Vicinity (Relocation Areas)

Map Unit	Formation	Acres	% of Relocation Total Area Acreage
1050	Slides	2.9947	0.09%
1100	Flows	52.9767	1.59%
1200	Complexes	175.8020	5.26%

Seiches A seiche is an oscillation of a body of water in an enclosed or semi-enclosed basin that varies in period, depending on the physical dimensions of the basin, from a few minutes to several hours, and in height from a few millimeters to a few meters. Seiches arise chiefly as a result of sudden local changes in atmospheric pressure, aided by wind and occasionally tidal currents. Seiches can also be triggered by strong earthquake ground motion or large landslides entering a body of water.

If Mount Shasta were to erupt again, volcanic ash could fall in the study area, though as described previously Mount Shasta is not likely to erupt large volumes of pumiceous ash (tephra) in the future. Minor seiches in Shasta Lake also could be generated by debris flows in the arms of the lake where its tributaries enter (City of Redding 2000). A large megathrust on the Cascadia subduction zone off the Pacific coast could generate enough ground shaking to generate a seiche in Shasta Lake.

Regardless of its cause, the effects of a seiche would depend on the local conditions at the time. If the reservoir were filled to capacity, there may be some overspill by way of the dam spillways. Substantial overtopping of the dam itself is extremely unlikely, as such an event would require a seiche more than six meters high, even if the reservoir were filled to capacity. Excess flows into the Sacramento River triggered by a seiche in Shasta Lake would be attenuated by Keswick Reservoir (City of Redding 2000).

Upper Sacramento River (Shasta Dam to Red Bluff) The upper Sacramento River portion of the primary study area could potentially be affected by geologic hazards in the region attributed to seismic hazards and volcanic eruptions and associated hazards. Mudflows, snow avalanches, slope instability, and seiches are not considered geologic hazards in this portion of the primary study area.

Seismic Hazards The Fault Activity Map of California and Adjacent Areas (Jennings 1994) places Quaternary faults in the eastern and southern portion of Shasta County and to the east and west of the upper Sacramento River. Quaternary faults are those with the most recent movement within the last 2 to 3 million years. The California Division of Mines and Geology (CDMG) (now called the California Geological Survey) considers Quaternary faults to be potentially active. The western portion of Shasta County has older, inactive faults on which future movement is unlikely. In 1972, the California State Legislature enacted the Alquist-Priolo Earthquake Fault Zoning Act (Alquist-Priolo Act) (California Public Resources Code Section 2622), which requires the State Geologist to delineate Earthquake Fault Zones around all known traces of potentially and recently active faults in California.

According to the Alquist-Priolo Act, Earthquake Fault Zones within Shasta County not included in the Shasta Lake and vicinity portion of the primary study area include the following:

- Portion of upper Butte Creek area north of Lassen Park (southern McArthur Fault).
- Generally, the Hat Creek Rim area, including portions of Cassel (Hat Creek Fault).
- Eastern portions of Fall River Valley, including eastern McArthur (McArthur Fault).

Shasta County although not as active as some areas of the State, is a seismically active region, but has not experienced significant property damage or loss of life from earthquakes in the past 120 years. The City of Redding (2005) reported that the maximum recorded intensities have reached Modified Mercalli VII, but have possibly been as great as Modified Mercalli VIII in one instance. The majority of intense seismic activity in Shasta County has occurred in the eastern half of the county, around Lassen Peak (City of Redding 2005).

The *Shasta County General Plan* states that the maximum intensity event expected to occur in eastern Shasta County is Modified Mercalli VIII (Shasta County 2004). In the western half of Shasta County, the maximum intensity is expected to be Modified Mercalli VII (City of Redding 2005). Shasta County is entirely within Seismic Zone 3 of the Uniform Building Code. Redding is an area of “moderate seismicity” and the Hat Creek and McArthur areas are of “moderate-to-high seismicity” (Shasta County 2004).

Processes that generally are grouped with ground failure include seismically induced landslides, liquefaction, lateral spreading and slumping, settlement, and lurch cracking. All of these processes involve a displacement of the ground surface from loss of strength or failure of the underlying materials during earthquake shaking. Landslides occur throughout Shasta County, are more prevalent in the eastern and northern portions of Shasta County than in the western portion of the county, and are commonly related to the sedimentary and volcanic rocks in these vicinities. Seismically induced landsliding is not considered a significant hazard in Shasta County (Shasta County 2004).

Liquefaction is the phenomenon in which soils experience a loss in strength and stiffness due to earthquake shaking or rapid loading, and the soils behave like a fluid. Liquefaction can result in the temporary transformation of a loose, saturated, granular soil from a solid into a semiliquefied state. This phenomenon is most likely in alluvial (geologically recent, unconsolidated sediments) and stream channel deposits, especially when the groundwater table is high. Areas of potential liquefaction are located along the Sacramento River and its tributaries in the north central valley area, referred to in this technical report as the South Central Region of the primary study area (Shasta County 2004).

South of Shasta County along the upper Sacramento River, potential surface faulting could be associated with the Great Valley thrust fault system, which is capable of earthquakes up to magnitude 6.8 along the west side of the Sacramento Valley. This fault system forms the boundary between the Coast Ranges and the Sacramento and San Joaquin Valleys.

The San Andreas Fault system is located west of the Sacramento and San Joaquin Valleys and is made up of a series of faults that lie along a 150-mile long northwest trending zone of seismicity. This zone is 10 – 45 miles west of the Sacramento Valley and extends from Suisun Bay past Lake Berryessa and Lake Pillsbury to near the latitude of Red Bluff. The Green Valley, Hunting Creek, Bartlett Springs, Round Valley, and Lake Mountain faults are the mapped active faults of the San Andreas Fault system most likely to affect the upper watersheds west of the Sacramento Valley. The faults in this system are capable of earthquakes of up to 7.1 in magnitude.

The Indian Valley Fault, located southeast of Lake Almanor and the Honey Lake Fault zone, located east of Lake Almanor are likely to affect the upper watersheds east of the Sacramento Valley, and are capable of a magnitude 6.9 earthquake. Surface rupture occurred in 1975 along the Cleveland Hill Fault south of Lake Oroville. The Foothills Fault system, which borders the east side of the Sacramento and San Joaquin valleys, is judged to be capable of a magnitude 6.5 earthquake.

Volcanic Eruptions and Associated Hazards As described in the Shasta Lake and vicinity discussion of volcanic eruptions and associated hazards above, three active centers of volcanic activity merit discussion in the primary study area, including the Medicine Lake Highlands, Lassen Peak, and Mount Shasta. Shasta County is at the southern end of the Cascade Range (described in the Geology of the Upper Sacramento River above). The most recent volcanic activity in Shasta County occurred between 1914 and 1917, when Lassen Peak erupted, producing lava flows, numerous ash falls, and a large mudflow. The mudflow, a result of melting snow and ash, flowed down Lost Creek and Hat Creek (Shasta County 2004).

There is no evidence of recent historic volcanic activity on Mount Shasta, but the danger from volcanic activity on the mountain may not be due to an eruption, but to mudflows, which have been recorded to travel more than 18 miles down the flanks of Shasta. It is unlikely that a large mudflow from Mount Shasta would endanger Shasta County (Shasta County 2004) or the upper Sacramento River between Shasta Dam and RBPP.

Extended Study Area

The following section describes the seismicity of the lower Sacramento River, the Delta, and the CVP/SWP service areas.

Lower Sacramento River and Delta The lower Sacramento River and Delta portion of the extended study area could potentially be affected by geologic hazards in the region attributed to seismic hazards. Volcanic eruptions and associated hazards, mudflows, snow avalanches, slope instability, and seiches are not considered geologic hazards in this portion of the extended area.

The nearest active fault to the Sacramento River along this segment of the extended study area is the Dunnigan Hills Fault, which has experienced fault displacement within the last 10,000 years (Jennings 1994). The Dunnigan Hills Fault runs along the Sacramento River and is located between 6 and 10 miles west of the river near the town of Dunnigan. The Cleveland Fault is located approximately 30 miles east of the Sacramento River near the city of Oroville. In addition to these active faults, a number of inactive faults as defined by the Alquist-Priolo Act, run along the Sacramento River. In addition, the Great Valley thrust fault system and San Andreas Fault System extend along the Sacramento River to the west, as described above for the upper Sacramento River portion of the primary study area.

Failure of the Delta levees is the primary threat to the region as a result of seismic activity. Levee failure would result from displacement and deformation caused by ground shaking and liquefaction of levee materials. Levees in the region consist of some sandy sections, which have low relative density and are highly susceptible to liquefaction. As a result, seismic risk to the Delta levees is variable across the Delta and depends on the proximity to the source of the earthquake, the conditions of the levee, and levee foundation.

A review of available historical information indicates that little damage to Delta levees has been caused by earthquakes. No report could be found to indicate that an island or tract had been flooded from an earthquake-induced levee failure. Further, no report could be found to indicate that significant damage had ever been induced by earthquake shaking. The minor damage that has been reported has not significantly jeopardized the stability of the Delta levee system.

This lack of severe earthquake-induced levee damage corresponds to the fact that no significant earthquake motion has ever been sustained in the Delta area since the construction of the levee system approximately a century ago. The 1906 San Francisco earthquake occurred 50 miles to the west, on the San Andreas Fault, and produced only minor levels of shaking in the Delta. Because the levees were not yet very high in 1906, these shaking levels posed little threat. Continued settlement and subsidence over the past 90 years, and the increasing height of levees needed for flood protection have, however, substantially changed this situation. Consequently, the lack of historical damage to date should not lead, necessarily, to a conclusion that the levee system is not vulnerable to moderate to strong earthquake shaking. The current levee system simply has never been significantly tested.

The Delta levees are located in a region of relatively low seismic activity compared to the Bay Area. The major strike-slip faults in the Bay Area (the San Andreas, Hayward, and Calaveras faults) are located more than 16 miles from the Delta. The less active Green Valley and Marsh Creek–Clayton Faults are more than 9 miles from the Delta region. Small but significant local faults are situated in the Delta, and there is a possibility that blind thrust faults occur along the west Delta.

CVP/SWP Service Areas The CVP/SWP service areas portion of the extended study area could potentially be affected by geologic hazards in the region attributed to seismic hazards. Volcanic eruptions and associated hazards, mudflows, snow avalanches, slope instability, and seiches are not considered geologic hazards in this portion of the extended study area. A number of active faults exists along the Sacramento and San Joaquin rivers in the CVP/SWP service areas.

Major earthquake activity has centered along the San Andreas Fault zone, including the great San Francisco earthquake of 1906. Since that earthquake, four events of magnitude 5.0 on the Richter scale or greater have occurred in the Bay region. The San Andreas and Hayward faults remain active, with evidence of recent slippage along both faults.

In the San Joaquin River region, the Great Valley thrust fault system forms the boundary between the Coast Ranges and the west boundary of the San Joaquin Valley. This fault system is capable of earthquakes up to magnitude 6.7 along the west side of the San Joaquin Valley.

The Diablo Range west of the valley is mainly subject to seismicity from northwest-trending faults associated with the right-lateral strike-slip San Andreas Fault system.

The mapped active faults of this system that are most likely to affect the upper watersheds west of the San Joaquin Valley are the Ortigalita Fault and the Greenville– Marsh Creek Fault. These faults lie along northwest-trending zones of seismicity 5 to 20 miles west of the San Joaquin Valley; each fault is capable of earthquakes up to magnitude 6.9.

Active faults likely to affect the upper watersheds east of the San Joaquin Valley include the Foothills Fault system and major faults along the east margin of the Sierra Nevada. The Foothills Fault system, which borders the east side of the northern part of the San Joaquin Valley, is judged to be capable of a magnitude 6.5 earthquake. Active faults along the east margin of the Sierra Nevada include the Owens Valley Fault, which ruptured in a magnitude 7.6 earthquake in 1872 and is within the Sierra Nevada Fault zone. Seismic activity along this fault zone can significantly affect the upper watersheds that drain to the San Joaquin Valley.

Active faults likely to affect the upper watersheds at the end of the San Joaquin Valley include the White Wolf Fault, which ruptured in 1952 with a magnitude 7.2 earthquake; the Garlock Fault, capable of a magnitude 7.3 earthquake; and several smaller faults 10 – 30 miles north of the White Wolf Fault.

Table 1-8 lists all of the reported faults, fault zones, and systems according to the California Geological Survey, located south– of– the– Delta in the CVP/SWP service areas (Bryant 2005).

Table 1-8. Faults, Fault Zones, and Systems Within the South-of-Delta Central Valley Project/State Water Project Service Areas

Fault Name	Fault Zone Name
NA	Beaumont Plain Fault Zone
NA	Blackwater Fault Zone
Burnt Mountain Fault	Burnt Mountain Fault Zone
NA	Calaveras Fault Zone
Calico Fault	Calico-Hidalgo Fault Zone
Camp Rock Fault	Camp Rock-Emerson-Copper Mountain Fault Zone
Chicken Hill Fault	Crafton Hills Fault Zone
East Montebello Hills Fault	East Montebello Hills Fault
Chino Fault	Elsinore Fault Zone
Eureka Peak Fault	Eureka Peak Fault
El Paso Fault	Garlock Fault Zone
Greenville Fault	Greenville Fault Zone
Black Mountain Fault	Harper Fault Zone
Crosley Fault	Hayward Fault Zone
Helendale Fault	Helendale-South Lockhart Fault Zone
Hollywood Fault	Hollywood Fault
Homestead Valley Fault	Homestead Valley Fault Zone
Hot Springs Fault	Hot Springs Fault
Kickapoo Fault	Johnson Valley Fault Zone
Johnson Valley Fault	Johnson Valley Fault Zone
Lenwood Fault	Lenwood-Lockhart Fault Zone
Llano Fault	Llano Fault
Long Canyon Fault	Long Canyon Fault
Los Positas Fault	Los Positas Fault
Solstice Fault	Malibu Coast Fault
Manix Fault	Manix Fault
Mount General Fault	Mount General Fault
Avalon-Compton Fault	Newport-Inglewood - Rose Canyon Fault Zone
Sky High Ranch Fault	North Frontal Fault Zone
North Frontal Fault Zone	North Frontal thrust system
Old Woman Springs Fault	Old Woman Springs Fault

Table 1-8. Faults, Fault Zones, and Systems Within the South– of– the– Delta Central Valley Project/State Water Project Service Areas (contd.)

Fault Name	Fault Zone Name
Palos Verdes Fault	Palos Verdes Fault Zone
Morongo Valley Fault	Pinto Mountain Fault Zone
Pleasanton Fault	Pleasanton Fault
Pleito Fault	Pleito Fault Zone
Quien Sabe Fault	Quien Sabe Fault Zone
Raymond Fault	Raymond Fault
Etiwanda Avenue Fault	Red Hill-Etiwanda Avenue Fault
NA	San Andreas Fault Zone
San Gabriel Fault	San Gabriel Fault Zone
San Gorgonio Pass Fault	San Gorgonio Pass Fault Zone
Casa Loma Fault	San Jacinto Fault Zone
Santa Monica Fault	Santa Monica Fault
Castro Fault	Sargent Fault Zone
Cucamonga Fault	Sierra Madre Fault Zone
Silver Reef Fault	Silver Reef Fault
Camarillo Fault	Simi-Santa Rosa Fault Zone
Tres Pinos Fault	Tres Pinos Fault
Verdugo Fault	Verdugo Fault
Verona Fault	Verona Fault
NA	Wheeler Ridge
Wright Road Fault	Wright Road Fault

Key:
NA = unnamed fault

1.1.3 Geomorphology

Geomorphology in the study area is described below for both the primary and extended study areas.

Primary Study Area

The following section describes geomorphology in the primary study area, including Shasta Lake and vicinity and the upper Sacramento River (Shasta Dam to Red Bluff).

Shasta Lake and Vicinity As described previously, most of the Shasta Lake and vicinity area is within the Klamath Geomorphic Province. The topography of the study area ranges from moderate to steep, and elevation ranges from approximately 1,070 feet to more than 6,000 feet above msl. The orientation and slopes of the ridges are controlled by the bedrock geology and structure. Generally speaking, the eastern slopes of the ridges are steeper than the western slopes. Hillslope gradient in the Shasta Lake and vicinity area ranges from 0 percent to more than 100 percent.

The regional stream network and boundaries of watersheds adjacent to Shasta Lake are shown in Figure 1-5. The boundaries of watersheds adjacent to Shasta Lake (shown in Figure 1-5) are the same as the boundaries of the area's 6th Field Hydrologic Unit Code (HUC) watersheds defined by USFS. Regional-scale characteristics of the streams that are tributary to Shasta Lake are presented in Figure 1-6, where they are organized by arm. The total area of watersheds draining to the lake on a regional scale is 6,665 square miles. Of this total, watersheds that are immediately adjacent and contribute directly to Shasta Lake (i.e., 6th Field HUC watersheds) occupy about 512 square miles (Table 1-9). These immediately adjacent watersheds include small portions of the five major tributaries to Shasta Lake (Big Backbone Creek, the Sacramento and McCloud rivers, Squaw Creek, and the Pit River) and small watersheds that are adjacent and directly contributory to the Main Body of the lake.

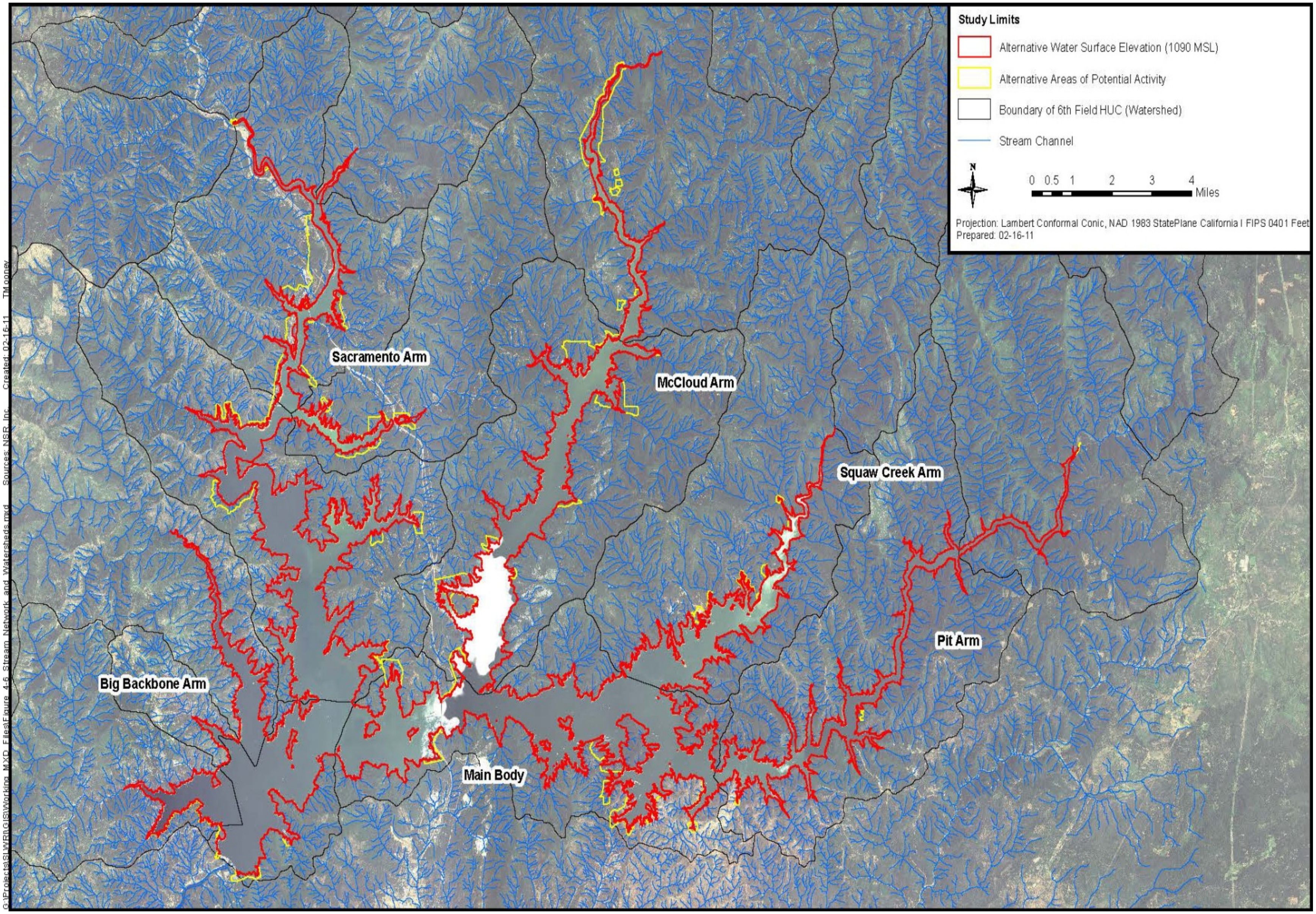
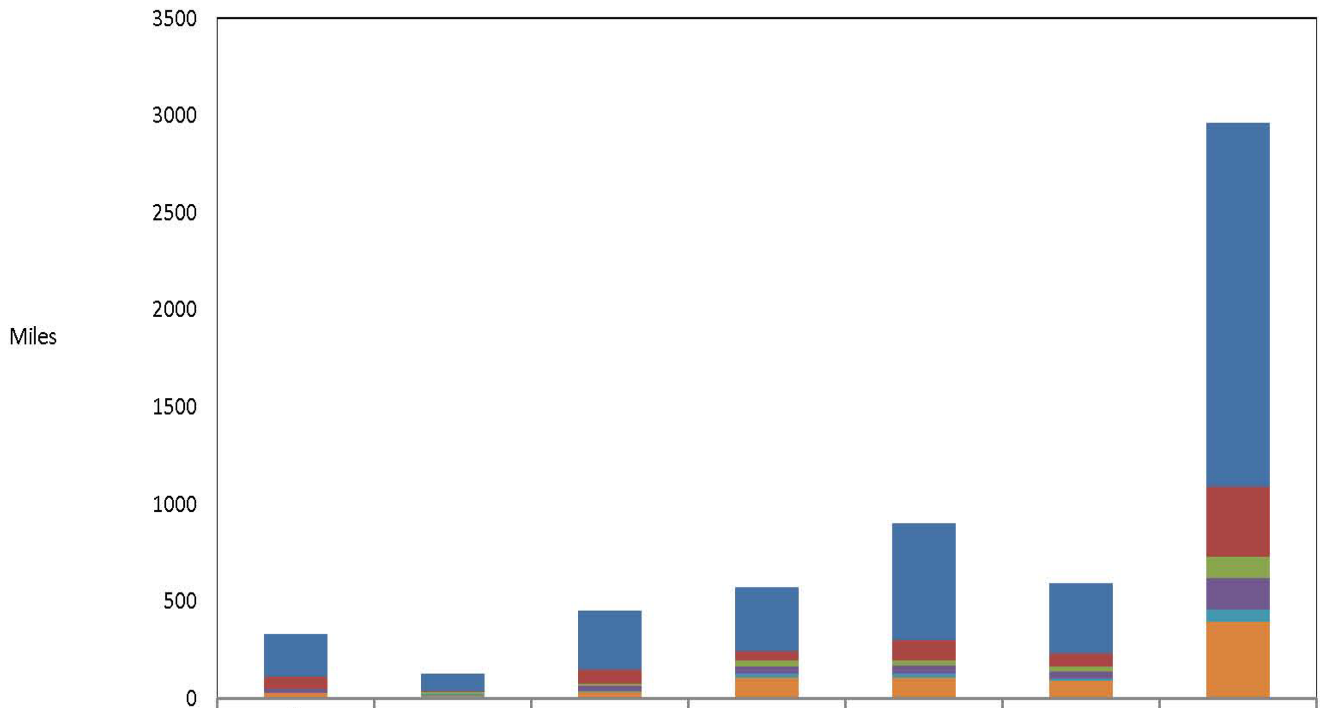


Figure 1-5. Regional Stream Network and Boundaries of Watersheds that are Adjacent to Shasta Lake and Vicinity



	Big Backbone Creek	Main Body	McCloud River	Pit River	Sacramento River	Squaw Creek	Total Length
Intermittent >10% Grade	214	83	297	321	597	355	1867
Pererrial >10% Grade	60	6	75	51	101	71	364
Intermittent 7-10% Grade	4	10	9	31	30	24	108
Pererrial 7-10% Grade	18	3	25	36	41	38	161
Intermittent <7% Grade	2	10	5	21	20	8	66
Pererrial <7% Grade	30	14	38	109	109	96	396

Figure 1-6. Regional-Scale Characteristics of Streams that are Tributary to Shasta

Table 1-9. Characteristics of Watersheds That Are Adjacent and Directly Tributary to Shasta Lake

Lake Arm	Drainage Area (square miles)	Stream Length (miles)	Drainage Density (miles/sq. miles)	Average Elevation (feet)	Max Elevation (feet)	Mean Annual Precipitation (inches)
Big Backbone Creek	60	325	5.4	2,185	4,633	74
Main Body	37	112	3.0	1,260	2,723	67
McCloud River	77	444	5.7	1,911	4,669	79
Pit River	100	551	5.5	1,700	3,246	73
Sacramento River	137	880	6.4	1,825	4,589	76
Squaw Creek	100	583	5.8	2,100	5,046	83
Total	512	2,903	5.7	1,885	5,046	77

In general, the stream networks adjacent and directly tributary to Shasta Lake are irregular and dendritic. The drainages are steep, and the drainage density ranges from 3.0 to 6.4 miles of stream per square mile of drainage area (Table 1-9). The drainage density is the lowest in the Main Body of the lake because this area has several small catchments. The density is the highest in the more well-defined arms, a function of their larger catchment areas of the tributary watersheds.

The lengths of streams within watersheds that are adjacent to Shasta Lake are also reported in Figure 1-6, where they again are aggregated by arm and further subdivided by flow regime (intermittent or perennial) and stream gradient. There are about 2,903 miles of ephemeral, intermittent, and perennial stream channels in these adjacent watersheds. Most (64 percent) of the stream channels are intermittent and have a stream slope greater than 10 percent. About 14 percent of the stream channels are perennial, with slopes less than 7 percent. Generally speaking, channels with gradients of less than 7 percent are known to support fish and other aquatic organisms. About 79 percent of these potential fish-bearing tributaries occur within the Sacramento River, Squaw Creek, and Pit arms.

Again, the values reported in Table 1-9 do not include large parts of the Sacramento River, Squaw Creek, Pit River, McCloud River, and Big Backbone Creek watersheds; only the “face drainages” within the arms themselves are included in the reported values.

Using existing data and information (NSR 2003), the following observations were made about the relative stability of the riverine reaches. Of the five main tributaries influencing Shasta Lake, all except Big Backbone Creek and the Sacramento River are underlain by shallow bedrock that limits channel incision. For this reason, Squaw Creek, and the Pit and McCloud rivers are relatively stable streams that are unlikely to change significantly in response to average floods. Although they occur infrequently, debris flows have the potential to substantially affect particularly shallow bedrock reaches of these tributaries, as is evident in Dekkas Creek. The Sacramento River and Big Backbone Creek are relatively dynamic because the channel bed has the potential to undergo physical changes in response to a moderate flood. Although Big Backbone Creek and Squaw Creek have similar watershed areas, Squaw Creek has more bedrock reaches than Big Backbone Creek and therefore is inherently more stable.

Upper Sacramento River (Shasta Dam to Red Bluff) The geomorphology of the Sacramento River is a product of several factors: the geology of the Sacramento Valley, hydrology, climate, vegetation, and human activity. Large flood events drive lateral channel migration and remove large flow impediments. Riparian vegetation stabilizes riverbanks and reduces water velocities, inducing deposition of eroded sediment. In the past, a balance existed between erosion and deposition along the Sacramento River. However, construction of dams, levees, and water projects has altered streamflow and other hydraulic characteristics of the Sacramento River. In some areas, human-induced changes have stabilized and contained the river, while in other reaches the loss of riparian vegetation has reduced sediment deposition and led to increased erosion.

The upper Sacramento River between Shasta Dam and Red Bluff is bounded and underlain by resistant volcanic and sedimentary deposits that confine the river, resulting in a relatively stable river course. This reach of river is characterized by steep vertical banks, and the river is primarily confined to its channel with limited overbank floodplain areas. There is limited meander of the river above Red Bluff.

Human-induced changes have also affected geomorphology of downstream tributaries to the Sacramento River in the study area. Major tributaries include Clear, Cottonwood and Cow Creeks.

Cow Creek The 275,000-acre Cow Creek Watershed is a large, generally uncontrolled tributary to the Sacramento River on the eastern side of the Sacramento River. The watershed is unique in that land ownership is almost evenly divided between commercial forestland, commercial agriculture, and small rural property owners, with minimum government ownership (WSRCD and CCWMG 2005).

Copper, coal, gravel and quarry stone have been mined from the Cow Creek watershed in the past. In contrast to other tributaries, gold was not discovered on the eastside of the Sacramento River in this area. However, the available timber and grazing lands on the eastern lands became primary supply areas for the initial gold and copper mining that occurred in other parts of the region (WSRCD and CCWMG 2001).

Gravel was mined in Little Cow Creek near Bella Vista (at Dry Creek and at Salt Creek), near Palo Cedro (Graystone Court and near Bloomingdale Road), and in the lower reaches of the main stem of Cow Creek. Mining of gravel in active floodways has likely reduced available spawning gravel in Little Cow Creek and the main stem of Cow Creek. Gravel removal may also have contributed to channel incisement (WSRCD and CCWMG 2005).

Ranching is currently a dominant land use in the watershed. Diversions of water for ranching activities significantly affect instream flow on the lower reaches of Cow Creek during the summer season (WSRCD and CCWMG 2005).

Major issues in the Cow Creek watershed are water quality and quantity for agriculture uses and natural barriers to fish passage (waterfalls) located at the break in geology limit anadromous fish passage into four of the five tributaries to Cow Creek. Geomorphic changes in Cow Creek (i.e. knickpoints) are attributed to natural breaks in the geology of the area and not to human activities. A review of historic aerial photos and available maps show that the configuration of the channel on the main stem has not changed significantly over the last century (WSRCD and CCWMG 2005).

Cottonwood Creek Cottonwood Creek is the largest undammed watershed on the west side of the Sacramento Valley. The watershed is characterized by a flashy hydrology, due to the absence of any flow regulating dams, low intra-annual storage resulting from a combination of very little recharge to aquifers in the upper reaches of the watershed and a small amount of snow pack (CH2M HILL 2005, 2007).

Human impacts on Cottonwood Creek began in the 1850s with placer and dredge gold mining operations. Two major gravel mines currently operate on Cottonwood Creek. The Shea Mine, which is in Shasta County, is immediately downstream of Interstate 5 and the Cottonwood Creek Sand and Gravel Mine (formerly XTRA), which is in Tehama County, is approximately 0.5 mile upstream of Interstate 5 (CH2M HILL, 2001).

Several reports suggest that persistent gravel mining combined with a flashy hydrology contribute to instability in channel conditions, excessive bank erosion and bed degradation in Cottonwood Creek (DWR 1992, Matthews 2003). Cross-sectional survey locations established by the USGS in 1983 and re-surveyed in 2002 show that considerable channel incision has occurred on Cottonwood Creek; in some areas, the channel is scoured to bedrock. These changes are likely caused by instream aggregate mining in excess of annual replenishment rates (Matthews 2003).

Clear Creek To characterize existing fluvial geomorphic conditions, Clear Creek is divided into upper clear Creek and lower Clear Creek, with the delineation occurring at Whiskeytown Dam. Upper Clear Creek (upstream of Whiskeytown Dam) is not discussed further in this section.

The lower Clear Creek watershed has been impacted by direct and indirect human activities for over a century. Widespread alterations to the watershed began in the 1800s, when the channel was placer mined and then dredged for gold, which caused extensive modifications to natural channel form and process by removing point bars, floodplains and riparian vegetation (WSRCD 1996). In some areas, the stream is incised completely down to clay hardpan or bedrock. Clear Creek is straight and highly entrenched in some areas; in others, it has multiple, braided channels due to direct and indirect human impacts (GMA 2007). Later, timber harvesting and associated road building caused excessive erosion throughout the watershed (WSRCD 1996).

The construction of McCormick-Saeltzer Dam in 1903 (dam removed in 2000) caused further changes in streamflow and sediment transport in the stream. Alteration of the natural flow and sediment regime in Clear Creek continued with construction of Whiskeytown Dam in 1963. Whiskeytown Dam greatly reduced the volume and magnitude of historical flows and effectively blocks the downstream transport of coarse sediment to lower Clear Creek (WSRCD 1996).

More recently, instream and off-channel aggregate mining began in 1950 and continued through the mid-1980s. Several hundred thousand cubic yards of aggregate were removed from Clear Creek below the former site of McCormick Saeltzer Dam, destroying the bankfull channel and in some areas completely removing the floodplain (WSRCD 1996).

Lower Clear Creek is the subject of several ongoing geomorphic studies and monitoring efforts, and fish habitat and channel restoration activities intended to offset past impacts on the watershed and stream channel by introducing spawning gravels into lower Clear Creek, implementing erosion control programs, reducing fuels within the watershed (USBR 2012). The Lower Clear Creek Floodway Rehabilitation Project, an extensive effort to restore the natural form and function of the Clear Creek channel and floodplain in areas highly affected by gold and aggregate mining.

Two headcuts have been observed on lower Clear Creek. The upstream-most headcut was observed in 2003, upstream of the former McCormick-Saeltzer Dam location. This headcut is the result of natural channel adjustment following dam removal in 2000 combined with a large storm event that occurred in December 2002 (UC Berkeley 2003). The headcut near the former dam site was observed again during monitoring activities in 2006 (GMA 2007). As of 2011, the channel appears to have stabilized in the vicinity of the former dam, with normal patterns of aggradation and deposition occurring within the reach (UC Berkeley 2011).

A second headcut has been observed farther downstream in Clear Creek, near the location of the Lower Clear Creek Floodway Rehabilitation Project. This headcut is migrating from the upstream end of the restoration site and has been attributed to past gravel mining and reduction of coarse sediment by upstream dams. In some areas above and below the site, the channel has incised to clay hardpan. Continued gravel augmentation upstream of the restoration area may reduce the rate of channel downcutting in the future (GMA 2007).

Extended Study Area

The following section describes the geomorphology in the extended study, including the lower Sacramento River and Delta and CVP/SWP service areas.

Lower Sacramento River and Delta Downstream from Red Bluff, the lower Sacramento River is relatively active and sinuous, meandering across alluvial deposits within a wide meander belt. The active channel consists of point bars composed of sand on the inside of meander bends, and is flanked by active floodplain and older terraces. Most of these features consist of easily eroded, unconsolidated alluvium; however, there are also outcrops of resistant, cemented alluvial units such as the Modesto and Riverbank formations. Geologic outcroppings and human-made structures, such as bridges and levees, act as local hydraulic controls and confine movement of much of the lower Sacramento River. Natural geomorphic processes in the Delta have been highly modified by changes to upstream hydrology (reservoirs and stream flow regulation) and construction of levees, channels, and other physical features.

In the channel itself, the bed is composed of gravel and sand (less gravel farther downstream), and point bars are composed of sand. The bottomlands flanking the channel consist of silts and sands (deposited from suspended load in floodwaters), commonly overlying channel gravels and sands. Higher, older surfaces consisting of (often cemented) Pleistocene deposits also are encountered.

The river channel migrates (maintaining roughly constant dimensions) across the floodplain to the limits of the meander belt, constrained only by outcrops of resistant units or artificial bank protection. As meander bends grow, they may become unstable and form cutoffs.

Since construction of Shasta Dam in the early 1940s, flood volumes on the river have been reduced, which has reduced the energy available for sediment transport. Straightening and a reduced rate of meander migration of the river may be associated with flow regulation because of Shasta Dam. The reduction in active channel dynamics is compounded by the physical effects of riprap bank protection structures, which typically eliminate shaded bank habitat and associated deep pools, and halt the natural processes of channel migration.

Sediment loads in the streams draining the upper watersheds have been artificially increased because of past and current logging and grazing practices. Historically, hydraulic mining in the Sierra Nevada near streams draining the upper watershed contributed sediment from gold mining. Both practices remove soil-stabilizing vegetation, create preferential drainages, and promote localized soil compaction. Erosive overland flow is enhanced by the loss of vegetation and compacted soils. Larger amounts of sediment are delivered to the streams from increased rates of soil erosion and from enhanced rates of mass movement, such as landslides. During high runoff events, the sharp increases in sediment yields can lead to widespread channel aggradation, which in turn can lead to lateral migration of the channels and increased rates of landsliding.

Where reservoirs have been created by dams, most of the sediment is trapped behind the dam and, during the life of the reservoir, will not be transported downstream from the dam. Where such sediment traps are not in place, the sediment load will be transferred downstream.

CVP/SWP Service Areas Geomorphology in the CVP/SWP service areas is a product of the same factors mentioned above–geology, hydrology and climate, vegetation, and human activity. Geomorphology in the CVP service areas is summarized in the descriptions of the primary study area and the lower Sacramento River and Delta portions of the extended study area.

Geomorphology in the SWP service areas extends into the southern geomorphic provinces of California and along part of the coast. The southern geomorphic provinces and coastal province include the Transverse Ranges, Peninsular Ranges, Mojave Desert, and Coast Ranges. The Transverse Ranges, composed of overlapping mountain blocks, consist of parallel and subparallel ranges and valleys. The Peninsular Ranges Geomorphic Province is composed of northwest to southeast trending fault blocks, extending from the Transverse Ranges into Mexico. The Peninsular Ranges are similar to the Sierra Nevada in that they have a gentle westerly slope and generally consist of steep eastern faces. The Mojave Desert Geomorphic Province topography is controlled by two faults: the San Andreas Fault, trending northwest to southeast, and the Garlock Fault, trending east to west (Jennings 1938). Before development of the Garlock Fault, sometime during the Miocene, the Mojave Desert was part of the Basin and Range Geomorphic Province. The Mojave Desert is now dominated by alluvial basins, which are aggrading surfaces from adjacent upland continental deposits (Norris and Webb 1990). The Coast Ranges have been greatly affected by plate tectonics. The Coast Ranges Geomorphic Province consists of elongate ranges and narrow valleys that run subparallel to the coast. Some of the mountain ranges along the Coast Range terminate abruptly at the sea (Norris and Webb 1990).

The mainstem San Joaquin River meanders within a meander belt of Recent alluvium. The river is characterized by an active channel, with point bars on the inside of meander bends, flanked by an active floodplain and older terraces. While most of these features consist of easily eroded, unconsolidated alluvial deposits, there are also outcrops of resistant, cemented alluvial units such as the Modesto and Riverbank formations.

The river channel migrates (maintaining roughly constant dimensions) across the floodplain to the limits of the meander belt, constrained only by outcroppings of resistant units or artificial bank protection. As meander bends grow, they may become unstable and form cutoffs, leaving oxbow lakes like those visible along lower reaches of the mainstem.

Sediment loads in streams draining the upper watersheds of the San Joaquin River region are similar to those described for the Sacramento River region.

1.1.4 Mineral Resources

This section describes the known mineral resources of commercial or otherwise documented economic value in both the primary and extended study areas. The mineral resources of concern include metals, industrial minerals (e.g., aggregate, sand, and gravel, oil and gas, and geothermal resources that would be of value to the region).

Primary Study Area

The following section describes the minerals resources in the primary study area, including Shasta Lake and vicinity and the upper Sacramento River.

Shasta Lake and Vicinity The following section describes mineral resources in the Shasta Lake and vicinity portion of the primary study area.

Metals The lands in the Shasta Lake and vicinity area are highly mineralized, with a history of significant mineral production. The Shasta Lake and vicinity area encompasses portions of two historic base metal mining districts, the west Shasta and east Shasta copper-zinc districts. The two districts focused on development of massive sulfide (Kuroko-type) deposits of submarine volcanogenic origin that formed contemporaneously with, and by the same process as, the host volcanic rocks. As in other areas in the Klamath Mountains, copper was by far the predominant commodity produced. Zinc, sulfur, iron, limestone, gold, and silver were produced as byproducts of copper production.

The Golinsky mine complex is located in the west Shasta district, approximately 7 miles west of Shasta Dam in the headwaters of Dry Creek and Little Backbone Creek. This inactive, abandoned mine complex is the only large historic producing mine within the Shasta Unit of the Whiskeytown-Shasta-Trinity NRA. Other mines within the NRA occur in the east Shasta district, concentrated between the McCloud and Squaw arms of Shasta Lake. The east Shasta district includes the Bully Hill, Copper City, and Rising Star mines, all of which are located in the Bully Hill area. These mines ceased operation before Shasta Dam was built.

These types of mineral deposits, in conjunction with the historic lode mining methods, have resulted in the discharge of toxic mine waste and acidic waters to Shasta Lake and some tributaries on a recurring basis (USFS 2000). The Golinsky mine complex has been subject to extensive remediation to reduce the discharge of toxic mine waste and acidic waters to Shasta Lake.

Industrial Minerals Industrial minerals occurring in the vicinity of Shasta Lake area include alluvial sand and gravel, crushed stone, volcanic cinders, limestone, and diatomite. In 2002, Shasta County produced 462,000 tons of sand and gravel, 852,000 tons of crushed stone (including limestone), and 51,000 tons of volcanic cinders. Limestone, used to produce Portland cement, and diatomite are not included in these figures.

The supply of Portland cement concrete grade alluvial sand and gravel within the region is more limited than the supply of non-Portland cement concrete grade material. The primary sources for alluvial sand and gravel near the Shasta Lake and vicinity area are the Sacramento River (downstream from Keswick Dam), Clear Creek, Cottonwood Creek, and Hat Creek. Crushed stone has been produced at a limestone quarry in Mountain Gate, a granite quarry in Keswick, an andesite quarry in Mountain Gate, a shale quarry in Oak Run, and two basalt quarries in the Lake Britton area near Burney. Volcanic cinders are produced at sites east of the Shasta Lake and vicinity area.

Limestone is used in a variety of industrial applications, but the bulk of limestone is used for the production of Portland cement concrete. Most of the limestone resources found in and near the Shasta Lake and vicinity area are located in fairly remote mountainous areas where extraction is uneconomical. However, significant mining of limestone for Portland cement concrete production occurs immediately south of Shasta Lake, in Mountain Gate. Diatomite is produced from sources near Lake Britton, east of the Shasta Lake and vicinity area.

Geothermal Resources Significant geothermal resources occur in the Medicine Lake Highlands, approximately 65 air miles northeast of Shasta Lake. The potential capacity of the Medicine Lake Highlands has been estimated at 480 megawatts (PacifiCorp 2010). Development of the Medicine Lake Highlands' geothermal resources has been the subject of extensive litigation of environmental issues and Native American concerns.

Upper Sacramento River (Shasta Dam to Red Bluff) Economically viable minerals found within the upper Sacramento River portion of the primary study area consist of alluvial sand and gravel, crushed stone, volcanic cinders, limestone, and diatomite. Additional mineral resources are found in the surrounding regions in Shasta and Tehama counties. These mineral resources include asbestos, barium, calcium, chromium, copper, gold, iron, lead, manganese, molybdenum, silver, and zinc (USGS 2005).

Extended Study Area

The following section describes mineral resources in the extended study area, including the lower Sacramento River and Delta and CVP/SWP service areas.

Lower Sacramento River and Delta Economically viable minerals found within the lower Sacramento River and Delta portion of the extended study area consist of alluvial sand and gravel, crushed stone, calcium, and clay. Additional mineral resources are found in the surrounding regions, including chromium, gold, granite, lithium, manganese, mercury, pumice, and silver (USGS 2005).

CVP/SWP Service Areas The USGS' mineral resources database indicates that numerous mineral resources found within the CVP and SWP service areas are or have been mined. These minerals include antimony, asbestos, barium, bismuth, boron, calcium, chromium, clay, copper, diatomite, feldspar, fluorite, gold, gypsum-anhydrite, halite, iron, lead, limestone, magnetite, manganese, marble, mercury, molybdenum, pumice, quartz, sand and gravel, silica, silver, slate, stone (crushed/broken), talc, tin, titanium, tungsten, uranium, and vanadium (USGS 2005).

1.1.5 Soils

Soils and erosion in the study area are described below for both the primary and extended study areas. Soils in the study area are described in the following sections in terms of their biomass productivity; susceptibility to erosion, subsidence, liquefaction, and expansion; and suitability for on-site application of waste material.

Soil biomass productivity is a measure of the capability of a site to produce biomass. The purpose of this management interpretation is to measure the site's productive capability when vegetative indicators (e.g., crop yields, site trees, and other vegetative biomass data) are not directly available (Miles 1999). Factors that influence soil biomass productivity include soil depth, parent material, available water-holding capacity, precipitation, soil temperature regime, aspect, and reaction (i.e., pH). Soil biomass productivity is characterized using four relative rankings: high, moderate, low, and non-productive.

The susceptibility of soil to erosion is characterized in terms of the soil's erosion hazard rating. The ratings indicate the hazards of topsoil loss in an unvegetated condition as might occur following disturbance by construction. Ratings are based on the soil erosion factor (K), slope, and content of rock fragments. The soil erosion factor (K) is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff, based primarily on soil texture but also considering structure, organic matter, and permeability.) Three ratings are recognized: slight, moderate, and severe. A rating of "slight" indicates that no post-disturbance acceleration of naturally occurring erosion is likely; "moderate" indicates that some acceleration of erosion is likely, and that simple erosion-control measures are needed; and "severe" indicates that significant erosion is expected, and that extensive erosion-control measures are needed.

Land subsidence is broadly defined to mean the sudden sinking or gradual downward settling of the land surface with little or no horizontal motion. Land subsidence can arise from a number of causes; the weathering characteristics of the underlying bedrock (e.g., as occurs for certain limestone formations); decomposition of the organic matter fraction of soils that are derived from peaty or mucky parent materials; aquifer-system compaction; underground mining; and natural compaction. Three processes account for most instances of water-related subsidence: compaction of aquifer systems, drainage and subsequent oxidation of organic soils, and dissolution and collapse of susceptible rocks.

Soil liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking or other rapid loading. Liquefaction occurs in saturated soils when the pore spaces between individual soil particles are completely filled with water. This water exerts a pressure on the soil particles that influences how tightly the particles themselves are pressed together. Prior to an earthquake, the water pressure is relatively low. However, earthquake shaking can cause the water pressure to increase to the point where the soil particles can readily move with respect to each other. When liquefaction occurs, the strength of soils decreases, and the ability of soils to support foundations for buildings and bridges is reduced.

Expansive soils are soils that contain water absorbing minerals, mainly “active” clays (e.g., montmorillonite). Such soils may expand by 10 percent or more when wetted. The cycle of shrinking and expanding exerts continual pressure on structures, and over time can reduce structural integrity. Soil susceptibility to expansion (i.e., shrinking and swelling) is tested using Uniform Building Code (UBC) Test Standard 18-1.

Soil suitability for onsite application of waste material focuses on the suitability of the soil to support the use of septic tanks or alternative wastewater disposal systems. Suitability interpretations are based on consideration of soil depth, permeability, rock content, depth to groundwater (including seasonally perched water), and slope.

Primary Study Area

The following sections describe soils and erosion in the primary study, including Shasta Lake and vicinity and the upper Sacramento River (Shasta Dam to Red Bluff).

Shasta Lake and Vicinity Soils in the Shasta Lake and vicinity area derive from materials weathered from metavolcanic and metasedimentary rocks and from intrusions of granitic rocks, serpentine, and basalt. Soils derived from the metavolcanic sources, such as greenstone, include the Goulding and Neuns families. Soils derived from metasedimentary materials include the Marpa family. Holland family soils are derived from metasedimentary and granitic rocks.

In general, metamorphosed rocks do not weather rapidly, and shallow soils are common in the area, especially on steep landscape positions. Soils from metamorphosed rocks generally contain large percentages of coarse fragments (e.g., gravels, cobbles, stones), which reduce their available water holding capacity and topsoil productivity. Granitic rocks may weather deeply, but soils derived from them may be droughty because of high amounts of coarse quartz grains and low content of “active” clay. Soils derived from granitic rocks commonly are highly susceptible to erosion.

Soil map units in the Shasta Lake and vicinity area are shown in Figure 1-7; Table 1-10 presents the mapping legend that accompanies the figure. The areal extent of soil map units within the Shasta Lake and vicinity area is presented in Table 1-11 for the portion of the area between 1,070 feet and 1,090 feet above msl (Impoundment Area), and in Table 1-12 for the portion potentially disturbed by construction activities (Relocation Areas). Sixty soil map units, comprising soil families and miscellaneous land types (e.g., Rock outcrop, limestone), are recognized to occur in the area. Common soil families are Marpa, Neuns, Goulding, and Holland. These are well-drained soils with fine loamy or loamy-skeletal (i.e., gravelly or cobbly) profiles.

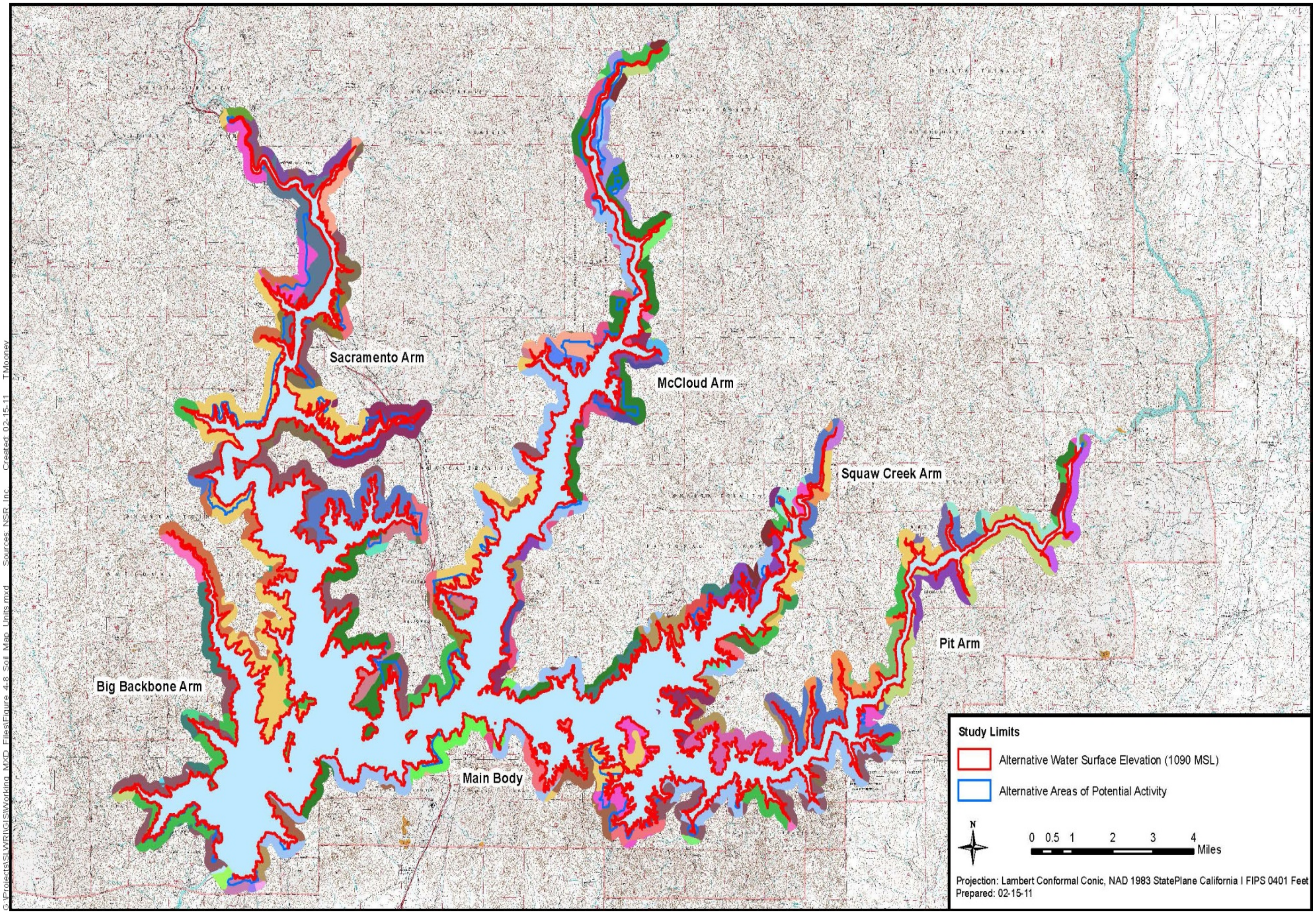


Figure 1-7. Soil Map Units – Shasta Lake and Vicinity

Table 1-10. Key to Soil Map Units – Shasta Lake and Vicinity

Map Unit, Map Unit Name
101, Holland-Goulding families association, 20 to 40 percent slopes.
102, Holland-Goulding families association, 40 to 60 percent slopes.
103, Holland-Goulding families association, 60 to 80 percent slopes.
104, Holland family-Holland family, deep complex, 20 to 40 percent slopes.
105, Holland family-Holland family, deep complex, 40 to 60 percent slopes.
107, Holland-Neuns families complex, 40 to 60 percent slopes.
109, Holland family, ashy, 0 to 20 percent slopes.
111, Holland, ashy-Leadmount families association, 0 to 20 percent slopes.
114, Holland, ashy-Washougal families complex, 25 to 65 percent slopes.
115, Holland family, deep, 0 to 20 percent slopes.
116, Holland family, deep, 20 to 40 percent slopes.
117, Holland family, deep, 40 to 60 percent slopes.
119, Holland family, deep-Holland families complex, 20 to 40 percent slopes.
120, Holland family, deep-Holland family complex, 40 to 60 percent slopes.
123, Holland, deep-Marpa families complex, 20 to 40 percent slopes.
127, Holland, deep-neuns families complex, 40 to 60 percent slopes.
133, Hugo family, 60 to 80 percent slopes.
139, Hugo-Neuns families complex, 60 to 80 percent slopes.
174, Marpa family, 20 to 40 percent slopes.
175, Marpa family, 40 to 60 percent slopes.
176, Marpa family, 60 to 80 percent slopes.
177, Marpa-Chawanakee families complex, 40 to 60 percent slopes.
178, Marpa-Goulding families association, 20 to 40 percent slopes.
179, Marpa-Goulding families association, 40 to 60 percent slopes.
18, Chaix family, 40 to 60 percent slopes.
180, Marpa-Goulding families association, 60 to 80 percent slopes.
182, Marpa-Holland, deep families complex, 20 to 40 percent slopes.
183, Marpa-holland, deep families complex, 40 to 60 percent slopes.
187, Marpa-Neuns families complex, 40 to 60 percent slopes.
188, Marpa-Neuns families complex, 60 to 80 percent slopes.
195, Millsholm family, 20 to 60 percent slopes.
203, Neuns family, 40 to 60 percent slopes.
204, Neuns family, 60 to 80 percent slopes.
209, Neuns-Goulding families association, 60 to 80 percent slopes.
214, Neuns-Holland, deep families complex, 40 to 80 percent slopes.
218, Neuns-Marpa families complex, 40 to 60 percent slopes.
219, Neuns-Marpa families complex, 60 to 80 percent slopes.
224, Neuns family-Typic Xerorthents association, 50 to 80 percent slopes.
228, Neuns family, deep-Neuns family complex, 40 to 70 percent slopes.
24, Chawanakee-Chaix families complex, 40 to 60 percent slopes.
250, Rock outcrop, limestone.

Table 1-10. Key to Soil Map Units – Shasta Lake and Vicinity (contd.)

Map Unit, Map Unit Name
251, Rock outcrop, metamorphic.
252, Rock outcrop, sedimentary.
259, Rock outcrop-Goulding family complex, 40 to 80 percent slopes.
27, Chawanakee family-Rock outcrop complex, 60 to 80 percent slopes.
35, Deadwood-Neuns families complex, 40 to 60 percent slopes.
61, Etsel family, 40 to 80 percent slopes.
79, Goulding family, 20 to 40 percent slopes.
80, Goulding family, 40 to 60 percent slopes.
81, Goulding family, 60 to 80 percent slopes
82, Goulding-Holland families association, 40 to 60 percent slopes.
83, Goulding-Marpa families association, 40 to 60 percent slopes.
85, Goulding family-Rock outcrop complex, 50 to 80 percent slopes
98, Holland family, 40 to 60 percent slopes.
99, Holland family, 60 to 80 percent slopes
AtE2sh, Auburn very stony clay loam, 30 to 50 percent slopes, eroded
AuF2sh, Auburn very rocky clay loam, 50 to 70 percent slopes, eroded
BoF3sh, Boomer very stony clay loam, 50 to 70 percent slopes, severely eroded
GeF2sh, Goulding very rocky loam, 50 to 70 percent slopes, eroded
W, Water

1 **Table 1-11. Areal Extent of Soil Map Units – Shasta Lake and Vicinity (Impoundment**
2 **Area)**

Map Unit	Map Unit Name	Acres	% of Total Subarea
18	Chaix family, 40-60% slopes	43.6	1.75%
27	Chawanakee family-Rock outcrop complex, 60-80% slopes	0.8	0.03%
35	Deadwood-Neuns families complex, 40-60% slopes	2.5	0.10%
61	Etsel family, 40-80% slopes	39.4	1.58%
79	Goulding family, 20-40% slopes	32.0	1.28%
80	Goulding family, 40-60% slopes	153.1	6.13%
81	Goudling family, 60-80% slopes	7.3	0.29%
82	Goulding-Holland families association, 40-60% slopes	45.3	1.81%
83	Goulding-Marpa families association, 40-60% slopes	118.5	4.74%
85	Goulding family-Rock outrcrop complex, 50-80% slopes	10.8	0.43%
98	Holland family, 40-60% slopes	3.6	0.14%
99	Holland family, 60-80% slopes	8.4	0.34%
101	Holland-Goulding families association, 20-40% slopes	66.5	2.66%
102	Holland-Goulding families association, 40-60% slopes	145.0	5.80%
103	Holland-Goulding families association, 60-80% slopes	4.6	0.18%
104	Holland family-Holland family, deep complex, 20-40% slopes	60.6	2.43%
105	Holland family-Holland family, deep complex, 40-60 % slopes	215.3	8.62%
109	Holland family, ashy, 0-22% slopes	0.1	0.00%
111	Holland, ashy-Leadmount families association, 0-20% slopes	93.4	3.74%
114	Holland, ashy-Washougal families complex, 25-65% slopes	6.2	0.25%
115	Holland family, deep, 0-20% slopes	38.6	1.54%
116	Holland family, deep, 20-40% slopes	8.5	0.34%
117	Holland family, deep, 40-60% slopes	32.1	1.29%
119	Holland family, deep-Holland families complex 20-40% slopes	111.5	4.46%
120	Holland family, deep-Holland family complex, 40-60% slopes	70.4	2.82%
123	Holland, deep-Marpa families complex, 20-40% slopes	66.7	2.67%
127	Holland, deep Neuns families complex, 40-60% slopes	4.1	0.16%
133	Hugo family, 60-80% slopes	5.2	0.21%
139	Hugo-Neuns families complex, 60-80% slopes	4.3	0.17%
174	Marpa family, 20-40% slopes	28.2	1.13%
175	Marpa family, 40-60% slopes	28.4	1.14%
177	Marpa-Chawanakee families complex, 40-60% slopes	47.1	1.89%
178	Marpa-Goulding families association, 20-40% slopes	74.7	2.99%
179	Marpa-Goulding families association, 40-60% slopes	309.8	12.40%
180	Marpa-Goulding families association, 60-80% slopes	10.2	0.41%

3

Table 1-11. Areal Extent of Soil Map Units – Shasta Lake and Vicinity (Impoundment Area) (contd.)

Map Unit	Map Unit Name	Acres	% of Total Subarea
182	Marpa-Holland, deep families complex, 20-40% slopes	89.1	3.57%
183	Marpa-Holland, deep families complex, 40-60% slopes	162.4	6.50%
187	Marpa-Neuns families complex, 40-60% slopes	5.6	0.22%
188	Marpa-Neuns families complex, 60-80% slopes	0.2	0.01%
195	Millsholm family, 20-60% slopes	39.7	1.59%
203	Neuns family, 40-60% slopes	7.6	0.30%
204	Neuns family, 60-80% slopes	43.5	1.74%
209	Neuns-Goulding families association, 60-80% slopes	1.7	0.07%
214	Neuns-Holland, deep families complex, 40-80% slopes	8.5	0.34%
218	Neuns-Marpa families complex, 40-60% slopes	1.1	0.04%
219	Neuns-Marpa families complex, 60-80% slopes	23.9	0.96%
250	Rock outcrop, limestone	9.3	0.37%
251	Rock outcrop, metamorphic	0.0	0.00%
259	Rock outcrop-Goulding family complex, 40-80% slopes	0.5	0.02%
AtE2sh	Auburn very stony clay loam, 30-50% slopes, eroded	0.1	0.01%
BoF3sh	Boomer very stony clay loam, 50-70% slopes, severely eroded	7.4	0.30%
W	Water	200.7	8.03%

Table 1-12. Areal Extent of Soil Map Units – Shasta Lake and Vicinity (Relocation Areas)

Map Unit	Map Unit Name	Acres	% of Total Subarea
18	Chaix family, 40-60% slopes	48.6	1.46%
35	Deadwood-Neuns families complex, 40-60% slopes	1.5	0.04%
61	Etsel family, 40-80% slopes	42.2	1.26%
79	Goulding family, 20-40% slopes	50.4	1.51%
80	Goulding family, 40-60% slopes	179.3	5.37%
82	Goulding-Holland families association, 40-60% slopes	13.9	0.42%
83	Goulding-Marpa families association, 40-60% slopes	6.6	0.20%
85	Goulding family-Rock outrcrop complex, 50-80% slopes	14.6	44.00%
102	Holland-Goulding families association, 40-60% slopes	280.0	8.38%
103	Holland-Goulding families association, 60-80% slopes	2.0	0.06%
104	Holland family-Holland family, deep complex, 20-40% slopes	79.1	2.37%
105	Holland family-Holland family, deep complex, 40-60 % slopes	170.9	5.12%
109	Holland family, ashy, 0-22% slopes	1.1	0.03%
111	Holland, ashy-Leadmount families association, 0-20% slopes	533.6	15.98%

Table 1-12. Areal Extent of Soil Map Units – Shasta Lake and Vicinity (Relocation Areas) (contd.)

Map Unit	Map Unit Name	Acres	% of Total Subarea
114	Holland, ashy-Washougal families complex, 25-65% slopes	1.5	0.05%
115	Holland family, deep, 0-20% slopes	120.0	3.59%
117	Holland family, deep, 40-60% slopes	71.2	2.13%
119	Holland family, deep-Holland families complex 20-40% slopes	163.5	4.90%
120	Holland family, deep-Holland family complex, 40-60% slopes	28.6	0.86%
123	Holland, deep-Marpa families complex, 20-40% slopes	86.8	2.60%
174	Marpa family, 20-40% slopes	150.5	4.51%
175	Marpa family, 40-60% slopes	17.0	0.51%
177	Marpa-Chawanakee families complex, 40-60% slopes	3.1	0.09%
178	Marpa-Goulding families association, 20-40% slopes	107.6	3.22%
179	Marpa-Goulding families association, 40-60% slopes	545.8	16.34%
180	Marpa-Goulding families association, 60-80% slopes	11.7	0.35%
182	Marpa-Holland, deep families complex, 20-40% slopes	247.0	7.40%
183	Marpa-Holland, deep families complex, 40-60% slopes	167.2	5.01%
195	Millsholm family, 20-60% slopes	36.7	1.10%
204	Neuns family, 60-80% slopes	19.4	0.58%
250	Rock outcrop, limestone	43.3	1.30%
259	Rock outcrop-Goulding family complex, 40-80% slopes	20.1	0.60%
AtE2sh	Auburn very stony clay loam, 30-50% slopes, eroded	2.7	0.08%
BoF3sh	Boomer very stony clay loam, 50-70% slopes, severely eroded	43.6	1.30%
W	Water	28.6	0.86%

Soil Biomass Productivity Soil biomass productivity in the Shasta-Trinity National Forest (STNF) ranges from nonproductive to high (USFS 1994). Using Forest Service Site Class (FSSC) as a surrogate metric for soil biomass productivity, approximately 36 percent of the Shasta Lake and vicinity by soils of low biomass productivity, about 39 percent by soils of moderate productivity, and about 13 percent by "nonproductive" soils and miscellaneous land types (e.g., rock outcrop). Soils of high biomass productivity are unlikely to occur in the Shasta Lake and vicinity area.

Soil Susceptibility to Erosion (Uplands) Interpretations of soil susceptibility to erosion are presented in Table 1-13 for the portion of the area between 1,070 feet and 1,090 feet above msl (Impoundment Area), and in Table 1-14 for the portion potentially disturbed by construction activities. Of the approximately 5,837 acres in the Shasta Lake and vicinity area, 5,377 acres (92 percent of total area) are assigned a hazard rating of severe.

Table 1-13. Summary of Soil Erosion Hazard – Shasta Lake and Vicinity (Impoundment Area)

Soil Erosion Hazard	Acres	% of Total Subarea
Moderate	38.55	1.54%
Severe	2248.81	90.03%
Not Rated	210.00	8.41%

Table 1-14. Summary of Soil Erosion Hazard – Shasta Lake and Vicinity (Relocation Areas)

Soil Erosion Hazard	Study Area (acres)	% of Total Subarea
Moderate	119.97	3.59%
Severe	3127.62	93.65%
Not Rated	92.01	2.76%

Soil Susceptibility to Erosion (Shoreline) There are more than 420 miles of shoreline around Shasta Lake. As described below under "Methods and Assumptions", a conceptual model was developed to quantify current erosion rates and predict future erosion rates (see Attachment 1, Shoreline Erosion Technical Memorandum).

Based on the model output, about 50 percent of the shoreline has a low erosion severity. The remaining shoreline has moderate (35 percent) to high (15 percent) erosion severity. Most of the shoreline that is exposed during routine drawdown periods (i.e., drawdown zone) has been subject to substantial erosion, and very little soil remains after more than 60 years of reservoir operations.

Soil Susceptibility to Subsidence Published interpretations of soil susceptibility to subsidence are generally not available for the Shasta Lake and vicinity area. The likelihood that subsidence would occur as a result decomposition of soil organic matter is low because of the absence of soils derived from peaty or mucky parent materials. Similarly, the likelihood of subsidence caused by aquifer-system compaction is low because of the absence of significant, widespread groundwater withdrawal in the Shasta Lake and vicinity area. Land subsidence has the potential to occur in areas underlain by highly-weatherable, carbonate-rich rocks (e.g., certain limestones), and in areas affected by underground construction.

Soil Susceptibility to Liquefaction Published interpretations of soil susceptibility to liquefaction are generally not available for the Shasta Lake and vicinity area. The likelihood that soil liquefaction would occur is low because of the absence of the necessary high groundwater conditions in the Shasta Lake and vicinity area.

Soil Susceptibility to Expansion Published interpretations of soil susceptibility to expansion (i.e., shrinking and swelling) are generally not available for most of the Shasta Lake and vicinity area. The likelihood that expansive soils occur is low because the weathering products derived from the local bedrock typically contain low concentrations of "active" clays (e.g., montmorillonite).

Soil Suitability for On-site Application of Waste Material Published interpretations of soil suitability for onsite application of waste material (i.e., capability to support use of septic tanks or alternative wastewater disposal systems) are generally not available for the Shasta Lake and vicinity area. In general, soils in the Shasta Lake and vicinity area are poorly suited to these uses because of shallow soil depth, high rock content, and excessive slope.

Upper Sacramento River (Shasta Dam to Red Bluff) The following section describes the susceptibility of soil in the upper Sacramento River portion of the primary study area to erosion (channel shoreline), erosion (wind), subsidence, liquefaction, and expansion.

Soils in the Sacramento River basin are divided into four physiographic groups: upland soils, terrace soils, valley land soils, and valley basin soils (Figure 1-8). Upland soils are prevalent in the hills and mountains of the region and are composed mainly of sedimentary sandstones, shales, and conglomerates originating from igneous rocks. Terrace and upland soils are predominant between Redding and Red Bluff; however, valley land soils border the Sacramento River through this area. Valley land and valley basin soils occupy most of the Sacramento Valley floor south of Red Bluff. Valley land soils consist of deep alluvial and aeolian soils that make up some of the best agricultural land in the state. The valley floor was once covered by an inland sea, and sediments were formed by deposits of marine silt followed by mild uplifting earth movements. After the main body of water disappeared, the Sacramento River began eroding and redepositing silt and sand in new alluvial fans.

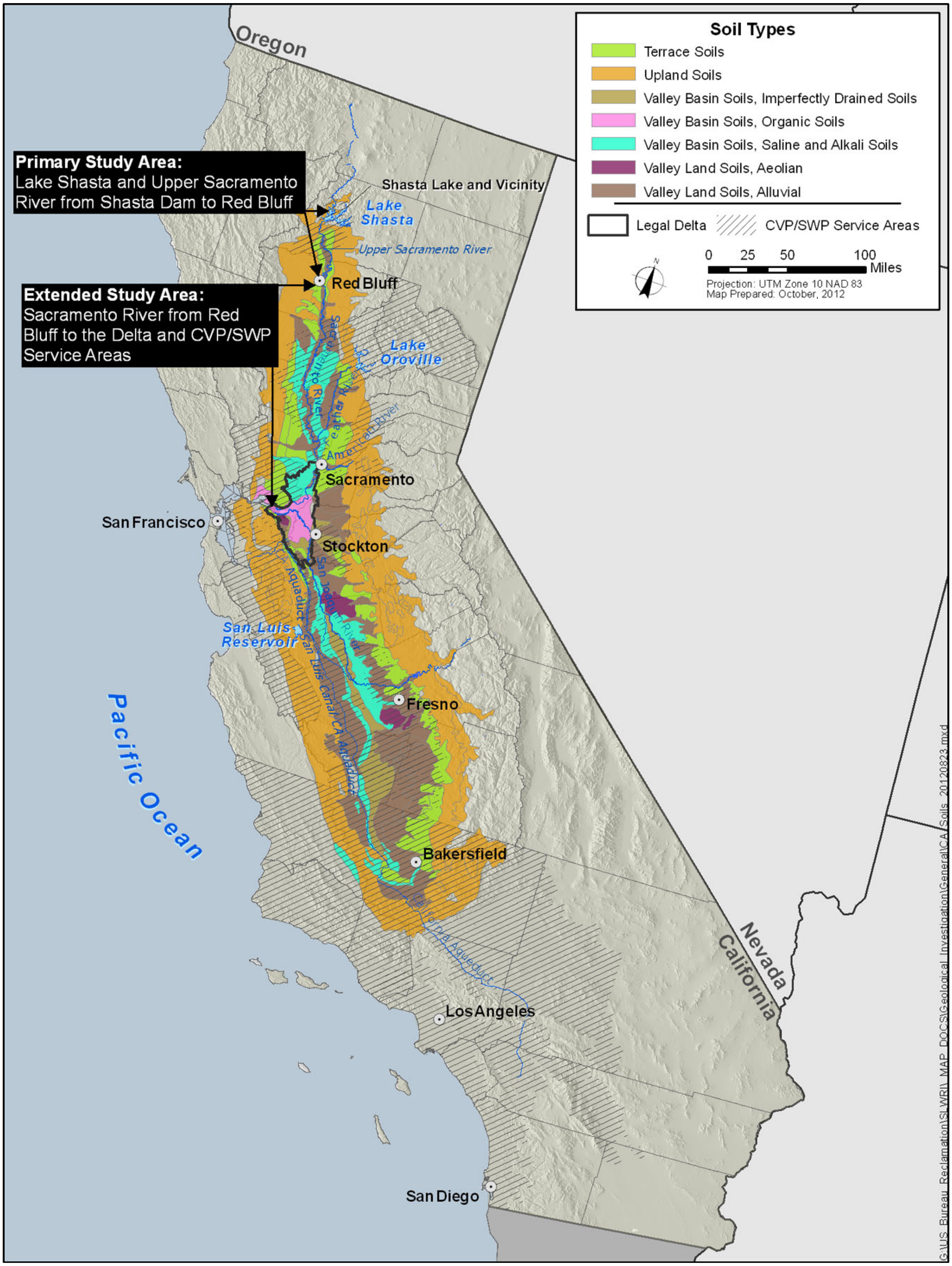


Figure 1-8. Soil Types of the Central Valley

The upper Sacramento River between Shasta Lake and Red Bluff is bounded and underlain by resistant volcanic and sedimentary deposits that confine the river, resulting in a relatively stable river course. This reach of river is characterized by steep vertical banks, and the river is primarily confined to its channel with limited overbank floodplain areas. There is limited meandering of the river above Red Bluff.

Soil Susceptibility to Erosion (Channel Shoreline) Sedimentation and erosion are natural processes of the mountainous streams that are tributary to Shasta Lake. The watershed above Shasta Lake is generally well forested, and erosion is moderate compared with more disturbed areas. However, watersheds for many of the tributaries of Shasta Lake have been significantly altered by a number of factors, including logging and hydraulic mining; construction of dams, roads, reservoirs; channel modifications; wildfires; and agricultural and urban activities. These cause sediment influxes and accelerated erosion. The changes in stream morphology often have negatively affected aquatic habitat and adjacent wetlands. The average annual flood flow was 121,000 cubic feet per second (cfs) at Red Bluff before construction of Shasta Dam (1879 through 1944), and 79,000 cfs after (1945 through 1993). The l0-year flood has been reduced from 218,000 to 134,000 cfs, which has reduced the energy available to transport sediment in the Sacramento River. Moreover, the sediment supply to the river has been reduced by sediment trapping in reservoirs, by mining of sand and gravel from channel beds, and by artificial protection of river banks. The erosion of the river banks had supplied sediment to the channel.

Shasta and Keswick dams have a significant influence on sediment transport in the Sacramento River because they block sediment that would normally be transported downstream. The result has been a net loss of coarse sediment, including salmon spawning gravels, in the Sacramento River below Keswick Dam. In the recent past, the U.S. Department of the Interior, Bureau of Reclamation (Reclamation), California Department of Water Resources, and California Department of Fish and Wildlife have cooperated to artificially replenish salmon spawning gravel downstream from Keswick Dam. In alluvial river sections, bank erosion and sediment deposition cause river channel migrations that are vital to maintaining instream and riparian habitats, but which can cause loss of agricultural lands and damage to roads and other structures. In the Sacramento River, these processes are most important in the major alluvial section of the river, which begins downstream from the RBPP. The river channel in the Keswick-to-RBPP reach is constrained by erosion-resistant formations and therefore is more stable.

Rates of bank erosion and channel migration have declined since 1946, presumably from change in peak flows and blockage of upstream sediment supply as a result of Shasta Dam, and from the construction of downstream bank protection projects. The channel sinuosity (ratio of channel length to valley length) also has decreased.

Rivers and floodplains are created, maintained, and modified by geomorphic processes whose rates and patterns are regulated through complex interactions of flow, sediment transport, and the properties of the channel and floodplain (including slope, erodibility, and morphology). Because large systems such as the Sacramento River are affected by the interaction of a wide variety of geomorphic processes, quantifying and understanding how they evolve can be complex.

The effects of management decisions on physical parameters (such as the magnitude and frequency of peak flow, for example) can often be quantified more or less straightforwardly. The implications for geomorphic processes and habitat dynamics are conversely much more difficult to determine, because relationships between process and form for channels and floodplains are typically complex and therefore not always easy to understand. Of particular concern are uncertainties in estimates of sediment supply, and the magnitude, timing, and duration of peak flows, which together are the fundamental regulators of sediment mobilization, bed scour, riparian recruitment, and bank erosion.

Soil Susceptibility to Erosion (Wind) Soil erodibility, climatic factors, soil surface roughness, width of field, and quantity of vegetative coverage affect the susceptibility of soils to wind erosion. Wind erosion leaves the soil shallower and can remove organic matter and needed plant nutrients. In addition, blowing soil particles can damage plants, particularly young plants. Blowing soils also can cause off-site problems such as reduced visibility and increased allergic reaction to dust.

Soil Susceptibility to Subsidence Land subsidence in the Sacramento Valley is localized and concentrated in areas of overdraft from groundwater pumping. Land subsidence had exceeded 1 foot by 1973 in two main areas in the southwestern part of the valley near Davis and Zamora; however, additional subsidence since then has not been reported.

Soil Susceptibility to Expansions Some soils have a potential to volumetrically swell when they absorb water and shrink when they dry out. Expansive soils, most commonly associated with montmorillonites, contain clays that volumetrically expand when moisture is absorbed into the crystal structure. Most of Shasta County is characterized by moderately expansive soils with areas of low expansiveness in the South Central Region and southeastern corner of the county. Small scattered areas of highly expansive soils exist in the mountains of the Western Upland, French Gulch, and North East Shasta County planning areas. The hazard associated with expansive soils is that areas of varying moisture or soil conditions can differentially expand or shrink, causing stresses on structures that lead to cracking or settling. This hazard is identifiable through standard soil tests. Its effects on structures can be mitigated by the requirements of proper engineering design and standard corrective measures.

Extended Study Area

Soils and erosion in the extended study area are described below.

Lower Sacramento River and Delta The following section describes the susceptibility of soil in the lower Sacramento River and Delta portion of the extended study are to erosion (channel shoreline), erosion (wind), subsidence, liquefaction, and expansion.

The soils of the Sacramento River basin are divided into four physiographic groups, as described above for the upper Sacramento River portion of the primary study area.

The soils of the Delta region vary primarily as a result of differences in geomorphological processes, climate, parent material, biological activity, topography, and time. The soils are divided into the following four general soil types:

- Delta organic soils and highly organic mineral soils
- Sacramento River and San Joaquin River deltaic soils
- Basin and basin rim soils
- Moderately well- to well-drained valley, terrace, and upland soils

The Delta region contains soils primarily with the required physical and chemical soil characteristics, growing season, drainage, and moisture supply necessary to qualify as Prime Farmland. This includes 80 – 90 percent of the area of organic and highly organic mineral soils, Sacramento River and San Joaquin River deltaic soils, and basin and basin rim soils. Most of the remaining soils of the Delta region qualify as farmland of Statewide Importance.

The Delta soils that have been most affected by agricultural development are the organic soils and highly organic mineral soils. These effects are caused by the flood protection of levees and the lowering of groundwater tables by pumps and drainage ditches to make production possible.

Soil Susceptibility to Erosion (Channel Shoreline) In the extended study area, the Sacramento River is a major alluvial river section that is active and sinuous, meandering across alluvial deposits within a wide meander belt. In alluvial river sections, bank erosion and sediment deposition cause migrations of the river channel. These migrations are extremely important in maintaining instream and riparian habitats, but also can cause loss of agricultural lands and damage to roads and other structures. Geologic outcroppings and human-made structures, such as bridges and levees, act as local hydraulic controls along the river. Bank protection, consisting primarily of rock riprap, has been placed along various sections of the Sacramento River to reduce erosion and river meandering.

The great quantities of sediment transported by the rivers into the Delta move primarily as suspended load. Of the estimated 5 million tons per year of sediment inflow into the Delta, about 80 percent originates from the Sacramento River and San Joaquin River drainages; the remainder is contributed by local streams. Approximately 15 – 30 percent of the sediment is deposited in the Delta; the balance moves into the San Francisco Bay system or out through CVP and SWP facilities.

Sediment circulation within the Bay-Delta system is complex because of the numerous interconnected channels, tidal flats, and bays, within which interaction of freshwater flows, tides, and winds produce an ever-changing pattern of sediment suspension and deposition. Pumping at the CVP and SWP Delta facilities alters this circulation of sediments within the system and may cause erosion of the bed and banks by inducing higher water velocities in the channels.

The mechanics of sediment transport in either saline or tidally affected streams, such as the lower Sacramento River and the Delta, are even more complex than in freshwater streams. This complexity results from changes in flow velocity, water density, flow direction, and water depth caused by changing tides. The Delta is primarily a depositional environment, but variations in water and sediment inflow may result in either erosion or deposition.

Erosion may occur when (1) the velocity of flow in a channel is increased, (2) the sediment inflow to a channel in equilibrium is reduced, or (3) predominance of flow in one direction is altered in a channel that experiences reverse flows. The actual rate of erosion depends on the composition of the material on the bed and banks, and on the amount of change in the factors listed previously in addition to other factors including subsidence or uplift.

Deposition is induced when conditions are the opposite of those favorable for erosion. The rate of deposition depends on the type and amount of sediment in suspension, the salinity, and the extent to which the transport capacity of the channel has been changed by reduction in flow velocity and channel size. Increasing salinity causes the suspended load of clay and silt particles to form aggregates that settle and deposit more rapidly than individual sediment particles. Deposition near Rio Vista may be caused by the convergence of the Sacramento River with the Deep Water Channel, forming a wider channel with resultant lower water velocities.

Flows induced by use of the Delta Cross Channel (DCC) have affected the North Fork of the Mokelumne River by eroding a rather deep channel near New Hope, thereby accelerating the need for riprap on the Mokelumne River levees. DCC flows that go down the South Fork pass through Dead Horse Cut and impinge on the Staten Island levee at a right angle, resulting in erosion of the bank in this area.

The discharges and velocities in the channels south of the San Joaquin River are influenced significantly by exports at the CVP and SWP pumping plants. Sediment deposition and gain from local drainage alter the amount and composition of the sediment transported in the channels. In addition, degradation or aggradation and widening or narrowing of certain channels may be occurring because of the higher velocities caused by pumping.

Soil Susceptibility to Erosion (Wind) The Delta's organic soils and highly organic mineral soils have wind erodibility ratings of 2 – 4 on a scale where 1 is most erodible and 8 is least erodible. The high wind erodibility of Delta soils is caused by the organic matter content of the soil. The rate of wind erosion is estimated at 0.1 inch per year.

Soil Susceptibility to Subsidence Subsidence of the Delta's organic soils and highly organic mineral soils continues to be a concern and could present a threat to the present land use of the Delta islands. Interior island subsidence is attributable primarily to biochemical oxidation of organic soil material as a result of long-term drainage and flood protection. The highest rates of subsidence occur in the central Delta islands, where organic matter content in the soils is highest.

Development of the islands resulted in subsidence of the islands' interiors and greater susceptibility of the topsoil to wind erosion. Subsidence, as it relates to Delta islands, refers generally to the falling level of the land surface from primarily the oxidation of peat soil. Levee settlement may be partially caused by peat oxidation if land adjacent to levees is not protected from subsidence.

Soil Susceptibility to Expansion Soils in the Lower Sacramento River and Delta portion of the extended study area vary from having low to high shrink-swell potential. In general, soils in the narrow corridor upstream along the Sacramento River have low shrink-swell potential according the U.S. Department of Agriculture's (USDA) State Soil Geographic (STATSGO) Database Soil Surveys, with the exception of some soils with moderate shrink-swell potential near the Red Bluff Pumping Plant (NRCS 1995). Downstream, the shrink-swell potential of soils near the Delta is generally classified by the STATSGO Soil Surveys as "high." The hazard associated with expansive soils is that areas of varying moisture or soil conditions can differentially expand or shrink, causing stresses on structures that lead to cracking or settling. This hazard is identifiable through standard soil tests. Its effects on structures can be mitigated through the requirements of proper engineering design and standard corrective measures.

CVP/SWP Service Areas The following section describes soil susceptibility to erosion (channel shoreline) and soil susceptibility to subsidence in the CVP/SWP service areas. As described above for the upper Sacramento River portion of the primary study area, soils in the CVP service areas are divided into four physiographic groups: valley land, valley basin, terrace land, and upland soils. According to USDA STATSGO Database, soils within the CVP/SWP service areas consist of clay, loam, silt, and sand, some of which is gravelly. The CVP/SWP service areas also consist of unweathered and weathered bedrock that is evident through outcrops at the ground surface (NRCS 1995).

San Joaquin River Region The following section describes soils and erosion in the San Joaquin River region.

Soils The San Joaquin River region contains four major landform types (each with its own characteristic soils):

- Floodplain
- Basin rim/basin floor
- Terraces
- Foothills and mountains

Floodplain lands contain two main soil types: alluvial soils and aeolian soils. The alluvial soils make up some of the best agricultural land in the State, whereas the aeolian soils are prone to wind erosion and are deficient in plant nutrients. Basin lands consist of poorly drained soils and of saline and alkali soils in the valley trough and on the basin rims. These soils are used mainly for pasture, rice, and cotton.

Areas above the valley floor contain terrace and foothill soils, which are primarily used for grazing and timberland.

The upper watersheds of the Sacramento and San Joaquin Valleys mainly drain foothills soils, which are found on the hilly to mountainous topography surrounding the San Joaquin Valley. Moderate depth to bedrock (20 – 40 inches) soils occur on both sides of the northern San Joaquin Valley, where the annual rainfall is intermediate to moderately high. Deep (greater than 40 inches) soils are the important timberlands of the area and occur in the high rainfall zones at the higher elevations in the mountains east of the valley. Shallow (less than 20 inches) soils, used for grazing, occur in the medium- to low-rainfall zone at lower elevations on both sides of the valley. Very shallow (less than 12 inches) soils are found on steep slopes, mainly at higher elevations. These soils are not useful for agriculture, grazing, or timber because of their very shallow depth, steep slopes, and stony texture. The geologic provinces comprising the San Joaquin River region include the Coast Ranges, Central Valley, and Sierra Nevada.

Soil Susceptibility to Subsidence After nearly 2 decades of little or no land subsidence, significant land subsidence was detected in the San Joaquin Valley along the Delta-Mendota Canal because of increased groundwater pumping during the 1987 through 1992 drought.

It was not until the 1920s that deep well pumping lowered the water table below the root zone of plants on the east side of the valley. Dry-farming practices were replaced with irrigated agriculture on the west side in the l940s, leading to the spreading and worsening of drainage problems on the west side of the valley and near the valley trough in the 1950s.

As a result of heavy pumping, groundwater levels declined by more than 300 feet in certain areas during the 1940s and 1950s. The groundwater level declines resulted in significant land subsidence over large areas. Significant historical land subsidence caused by excessive groundwater pumping has been observed in the Los Banos-Kettleman Hills area, the Tulare-Wasco area, and the Arvin-Maricopa area.

Bay Region The following section describes soils and erosion in the Bay region.

Soils The bay region can be divided into four major landform types (each with characteristic soils):

- Basin floor/basin rim
- Floodplain/valley land
- Terraces
- Foothills and mountains

Basin lands consist of organic-rich saline soils adjacent to the bay and poorly drained soils somewhat farther from the bay. Valley land soils generally are found on gently sloping alluvial fans that surround the floodplain and basin lands. These soils, along with floodplain alluvial soils, represent the most important agricultural group of soils in California. In the Bay Area, most of the floodplain and valley land soils have been urbanized.

Terrace land soils are found along the southeastern edge of the Bay Area at elevations of 5 to 100 feet above the valley floor. Most of these soils are moderately dense soils of neutral reaction.

Soils of the foothills and mountains that surround the bay are formed through the decomposition and disintegration of the underlying parent material. The most prevalent foothills soil group has a moderate depth to bedrock (20 – 40 inches), with lesser amounts of the deep depth (greater than 40 inches) and shallow depth (less than 12 inches) to bedrock soil groups present. Moderate-depth soils generally are dark colored and fairly high in organic matter, and constitute some of the best natural grazing lands of the state. Deep soils occur in the high rainfall zones at the higher elevations in the Coast Ranges. They generally support forest lands in the bay region and are characterized by acid reaction and depths to bedrock of 3 – 6 feet. Shallow soils occur in the medium-to low-rainfall zone. They are loamy in character and are used principally for grazing.

Soil salinity problems occur primarily in the western and southern portions of the San Joaquin Valley. Most soils in this region were derived from marine sediments of the Coast Ranges, which contain salts and potentially toxic trace elements such as arsenic, boron, molybdenum, and selenium. Soil salinity problems in the San Joaquin Valley have been, and continue to be, intensified by poor soil drainage, insufficient water supplies for adequate leaching, poor-quality (high-salinity) applied irrigation water, high water tables, and an arid climate. A 1984 study estimated that about 2.4 million of the 7.5 million acres of irrigated cropland in the Central Valley were adversely affected by soil salinity.

Soil Susceptibility to Erosion (Wind) The major source of suspended sediment in the bay is outflow from the Delta. Approximately three-quarters of the suspended sediment enters the bay with the high winter and early spring flood flows. The highest suspended sediment and turbidity levels occur during these periods. Although much of the suspended sediment begins to aggregate at the salinity gradient, and deposit in the shallow areas of Suisun and San Pablo bays, high seasonal flows can transport incoming sediment as far as the Central and South bays.

Sediments deposited in the shallower regions are resuspended by wave and wind action. Approximately 15 times the material that enters the bay is resuspended each year. Resuspension of sediment is the most important process for maintaining turbidities in the bay from late spring through fall.

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Draft

Attachment 1
Shoreline Erosion Technical Memorandum

Geologic Technical Report

Shasta Lake Water Resources Investigation, California

Prepared by:

United States Department of the Interior
Bureau of Reclamation
Mid-Pacific Region

U.S. Department of the Interior
United States Department of the Interior **June 2013**

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Abbreviations and Acronyms

CP	Comprehensive Plan
NSR	North State Resources, Inc.
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
RED	Redding, California weather station
SLWRI	Shasta Lake Water Resources Investigation
USACE	U.S. Army Corps of Engineers

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Chapter 1 Introduction

North State Resources, Inc. (NSR) prepared this Technical Memorandum to document an analysis of existing shoreline erosion rates of Shasta Lake and predicted rates associated with raising Shasta Dam. Data collected for this study will be used to assist the U.S. Department of the Interior, Bureau of Reclamation (Reclamation) in determining potential impacts to the environment related to the Shasta Lake Water Resources Investigation (SLWRI) report. The following evaluation is based on a review of existing literature and data, supplemented with site specific information obtained from the shoreline erosion investigation.

This memorandum is organized as follows:

- Introduction
- Methods
- Results and Discussion

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Chapter 2 Methods

2.1 Shoreline Erosion Conceptual Model

This analysis included the development of a conceptual model of the spatial and temporal components of shoreline erosion as a framework for field investigations, quantifying present erosion rates, and predicting future erosion rates. This is a process based model where the primary causes of shoreline erosion are characterized and the external erosion triggers are used to weight the relative erodibility of the shoreline. This model was developed using results from similar studies, the available precipitation, wind, and lake level data, engineering properties of the bedrock geology and soils, shoreline and hillslope topography, and measured erosion processes and rates from sequential historical aerial photographs and field investigations. There are very few existing reservoir shoreline erosion studies for a reservoir as large as Shasta Lake available to use as background and support for this analysis. This analysis uses readily available references to help characterize the process of shoreline erosion, verify the predicted shoreline erosion rates, and design mitigation measures.

2.1.1 Shoreline Zone Classification

The shoreline is broken into two zones for modeling purposes which helps account for the episodic nature of erosional events. The near shore zone is classified as the area above the 1,070 foot contour and represents the "bath tub" ring around the reservoir (Figure 2-1). The drawdown zone is classified as the area between the 1,070 foot contour and the 1,020 foot contour. The latter contour is used to represent the drawdown level that typically occurs to meet the U.S. Army Corps of Engineers (USACE) flood storage capacity requirements. The near shore zone is eroded by wave action when the reservoir is full. During drawdown periods, this zone erodes as a result of upland surface runoff, subsurface flow, and fluvial incision along stream channels and gullies. The drawdown zone is subject to reoccurring erosional forces as the reservoir level falls and rises. Wave action caused by wind and boat traffic is the dominant erosional force within this zone (Figure 2-1). This zone is also a depositional area during full pool conditions. Sediment deposited in this zone is remobilized as the reservoir is drawn down. Channel incision is common in this zone especially where stream channels intersect it, or the slope is steep and convergent.

Figure 2-1. Picture of Shoreline Showing near Shore and Drawdown Zones

2.1.2 Shoreline Erosion Lithotopo Units

The climate, bedrock geology, soils, and topography were used to stratify the shoreline into lithotopo units to spatially compartmentalize the landscape into areas with similar erosion processes and rates (Montgomery 1999). These units are used as the basis for the potential shoreline erosion calculations. Around Shasta Lake, the rate of shoreline erosion is highly dependent on the engineering properties of the underlying geology. These properties control the hillslope steepness and shape of the local topography, and influences the types and density of vegetation. Field measured erosion volumes at selected sites around the reservoir were used to predict erosion from areas of shoreline with similar geology, soil, slope, and vegetation characteristics. For the final potential erosion calculations, slope gradient was used to predict the erosion rate for areas not included in the field investigations.

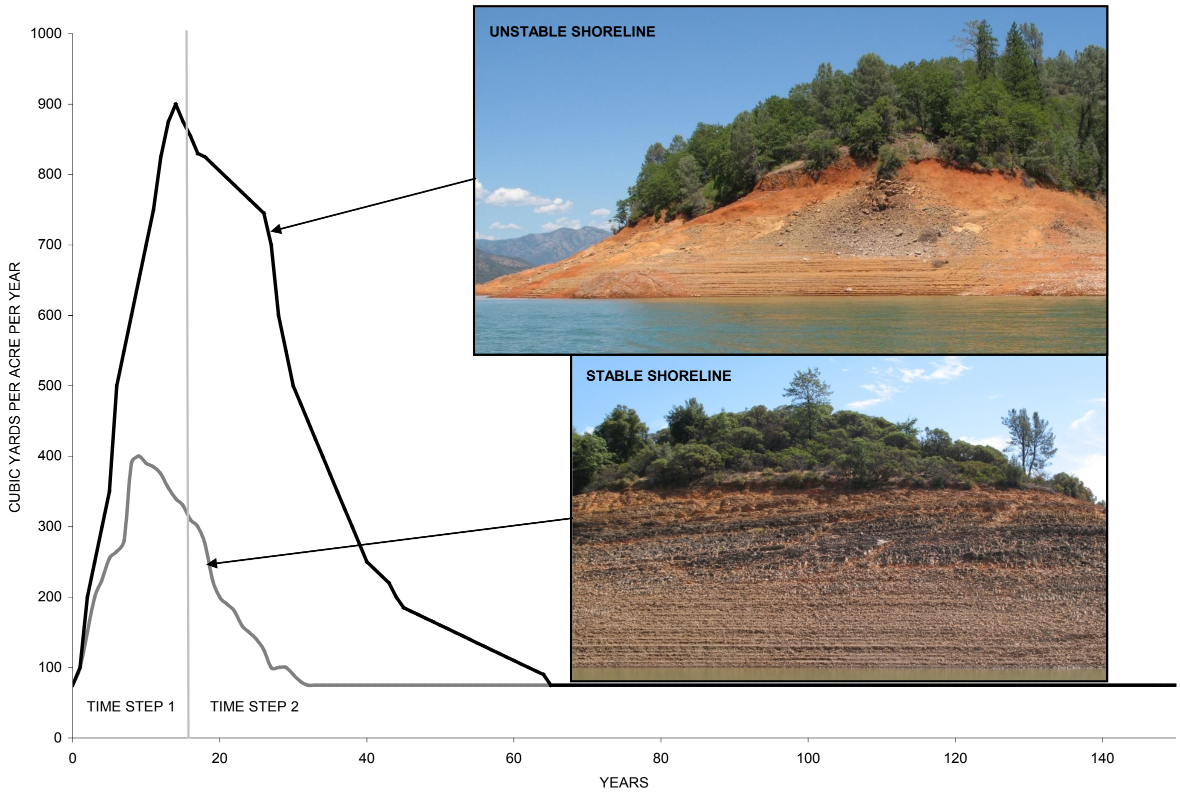
2.1.3 Shoreline Erosion Formation Time Steps

Shoreline formation is triggered when a reservoir is filled for the first time, and the long-term rate of shoreline erosion typically decreases as a reservoir ages (Morris and Fan 1997). The shoreline configuration is a function of both the landscape being inundated, size of the reservoir, and frequency and magnitude of fluctuations in reservoir level.

The lithotopo units described previously are used to represent the spatial distribution of shoreline erosion. In an attempt to represent the temporal component of shoreline erosion, this model compartmentalized shoreline development into three time steps. The first time step lasts for about 15 years and is when most of the erosion occurs (Morris and Fan 1997) (Figure 2-2). During this time, the inundated soils are fully saturated: as a result they lose cohesion and are subject to rapid erosion, transport, and deposition. Shoreline exposed in this drawdown zone is typically eroded to bedrock or resistant soil layers leaving an exposed surface that supports a limited amount of vegetation. Within this zone, stream channels and gullies rapidly incise into the underlying soil and rock.

The second time step can last between about 0 and 150 years. During this time the stable shoreline topography is developing through a sequence of slope forming events (Figure 2-2). For modeling purposes, the types of slope forming events were classified by lithotopo unit since there are several common processes that trigger and control erosion. The shoreline erosion inventory data suggest that stable hillslopes are typically associated with shallow soils on coherent bedrock forming steep topography (i.e., > 65 percent slope gradient), and unstable hillslopes are associated with deep soils on moderately steep areas (i.e., between 30 percent and 65 percent). Around Shasta Lake, stable shoreline formed rapidly during the first 15 years after inundation. Conversely, about 60 years later unstable hillslopes are still are still responding to erosional forces, and in various locations continue to erode at a very high rate (i.e., > 900 cubic yards/acre/year).

The third time step is used to represent the time frame when the shoreline slope is stable and the soil shear strength remains greater than the shear stresses acting on the slope. During this time frame, the erosion rate continues to decrease and eventually equals the upslope erosion rates. This analysis assumes that most of the shoreline around Shasta Lake will become stable as the reservoir ages, and the data suggests that currently, about half of the shoreline has reached equilibrium.



Note: Approximate Location of Time Steps one and two shown. These Curves do not Represent Actual Time Series of Erosion

Figure 2-2. Hypothetical Curves Showing Short- and Long-Term Shoreline Erosion Rates for Stable and Unstable Lithotopo Units

2.1.4 Shoreline Erosion Causes and Triggers

This analysis classified slope forming events within the confines of the primary and external factors controlling slope stability. Unstable slopes occur when the shear strength of a soil layer is less than the shear stress acting on the layer. Shear strength is influenced by the soil cohesion, the soil to rock contact, vegetation types and root depths, and subsurface moisture content (Sidle and Ochiai 2006). For modeling purposes, this analysis assumes that the primary factors that cause slope failure along the shoreline are related to the climate, topography, engineering properties of the bedrock geology and soils, and vegetation. It also assumes that external factors that trigger slope failure include erosion at the toe of the slope due to wave action and surface runoff, vegetation removal by land management and wildland fire, and increased groundwater levels as a result of upslope seasonal groundwater recharge and lake level management. Shoreline vegetation is most often altered by fire: however, land development; mining; and logging activities remove shoreline vegetation as well.

Reshaping of the shoreline toe by wave action reduces the shear strength of the slope and is one of the main external factors triggering shoreline erosion (Morris and Fan 1997 and Elci and Work 2003). These events occur when the reservoir is full and waves caused by wind and boat traffic are able to erode the exposed soils. For Shasta Lake, annual water level data show that the reservoir is likely to fill 20 percent of the time, the reservoir is normally filled between mid-April and mid-May, and it remains full for two to four weeks on average. During wet water years when the reservoir is filled, the shoreline toe is eroded by waves. Typically, during this time period the upland soils are not fully saturated like they as they would be during the wet season. Subsequently, during dryer years when the reservoir does not fill the slopes readjust to a stable angle. In extreme cases, debris flows and slides have formed that continue to migrate upslope and laterally (Figure 2-2). Typically, it takes several decades for these mass wasting features to reach a stable balance between shear strength and shear stress.

There are several other external disturbance factors that can trigger shoreline erosion as a result of their impact on wave action, surface runoff, upland erosion, and groundwater recharge. These processes can both re-activate shoreline erosion and extend the amount of time it takes for a given slope to reach a state of equilibrium.

Boat traffic is a significant source of wave action that causes erosion along the shoreline. Since Shasta Lake is in a drawn down from about June through November, boat generated waves provide erosional forces during the timeframe beyond the period when winter storms are generating wave action.

Land development around Shasta Lake triggers shoreline erosion. Grading, vegetation removal, and paving increase the hardscape around the shoreline and can cause increased surface runoff and erosion. Roads associated with land development can impact the surface runoff patterns and concentrate flow causing channel incision and gully erosion. Landscape disturbances associated with mining activities contribute to shoreline erosion as well. Around the reservoir, large areas were denuded of vegetation and continue to be subjected to erosional processes 80 years after the mining operations ceased. Hard rock and surface mine operations have left a footprint on the hillslopes around Shasta Lake. One of the main impacts is from smelting on soil productivity. Many of these disturbances precede dam construction. Several large landslides have formed below mined areas and the shoreline is destabilized as a result.

Disturbance associated with severe wildland fire contribute to shoreline erosion. Large severe fires strip the uplands of vegetation and often cook the soils making them hydrophobic (less capable of absorbing precipitation). Following severe fire, upland runoff and erosion increase and cause channel incision and gully erosion along the near shore and drawdown zones. Removal of vegetation by fire along the shoreline reduces the shear strength of shoreline slopes as well.

2.2 Shoreline Erosion Field Inventory

2.2.1 Shoreline Erosion Reconnaissance Inventory

The shoreline erosion reconnaissance inventory was conducted on all of the arms of Shasta Lake. Inventory sites were chosen to characterize major and minor erosional features. Physical and erosional characteristics were gathered at each site by manual measurement or direct observation and then recorded. The categories of physical and erosional features are listed in Table 2-1. Where applicable, the descriptions and examples of the features are used in lieu of an actual method description because the methods used for characterizing some features are often based on an assessment of the terrain by the observer. These assessments often compared the features at each site to a field identified type locality for the varying grades of each feature. The data collected at each site was further used to delineate which sites to use as erosion plot sites and to determine which characteristics had the highest positive correlation with erosion rates.

Table 2-1. Summary of Shoreline Erosion Reconnaissance Inventory Site Counts by Feature and Lake Arm

Feature Attributes		Lake Arms							Totals Summary	
Feature	**Feature Category**	*Big Backbone Creek Arm*	*Main Body East Arm*	*Main Body West Arm*	*McCloud River Arm*	*Pit River Arm*	*Sacramento River Arm*	*Squaw Creek Arm*	**Site Count**	**% of Total Sites (1538 sites)**
Erosion Severity	High	23	50	43	57	10	64	17	264	17%
	Moderate	42	118	38	119	67	103	33	520	34%
	Low	62	195	30	125	129	146	65	752	49%
Slope Height	0'-3'	62	198	31	123	108	137	57	716	47%
	3'-6'	34	110	35	108	85	103	37	512	33%
	> 6'	31	55	45	70	13	73	21	308	20%
Erosion Activity	Chronic	125	363	110	295	204	308	109	1514	98%
	Episodic	13	45	40	53	27	47	5	230	15%
	Historic	12	4	1	6	1	3	2	29	2%
Dominant Erosion Types	Mass Wasting	29	70	50	82	41	64	3	339	22%
	Surface	13	88	16	64	30	66	1	278	18%
	Rill	0	0	0	0	1	1	0	2	0%
	Ravel	48	211	63	139	110	160	11	742	48%
	Gulley	15	2	1	6	0	4	0	28	2%
	Sapping	24	14	7	35	28	42	1	151	10%
	Wave	67	354	106	267	178	265	13	1250	81%
	Other	0	0	0	0	1	6	0	7	0%
Slope Angle	0-30%	43	165	42	103	40	122	51	566	37%
	31-60%	70	171	61	164	114	163	50	793	52%
	>61%	14	27	7	34	52	29	14	177	12%
Slope Break Type	Oversteep	80	197	49	82	60	116	52	636	41%
	Undercut	7	60	21	78	53	64	33	316	21%
	Both	36	99	38	132	87	129	29	550	36%
Material Types	Bedrock	3	1	2	3	4	31	6	50	3%
	Cobble-Boulder	21	2	1	19	35	46	2	126	8%
	Soil	103	361	108	281	169	249	108	1379	90%
Slope Armor	0-30%	101	354	110	276	173	260	107	1381	90%
	31-70%	26	9	1	24	33	53	6	152	10%
	>70%				1			2	3	0%
Vegetative Cover	Dense	9	71	53	75	40	65	14	327	21%
	Moderate	94	214	54	190	136	205	48	941	61%
	Sparse	23	78	4	36	30	43	52	266	17%

Erosion activity qualitatively measures the frequency of erosion at each site, and is divided into chronic, episodic, and historic frequency classes. The activity at each site was determined by evidence of recent erosional processes. For example, a site where silt is visibly deposited in the lake due to wave erosion is called chronic erosion activity. A site with a large gully incised into the slope with no visible signs of erosion is called episodic erosion activity. A site with a large slump with an established stand of mature vegetation growing on the slump block and the scarp is called historic erosion activity.

The dominant erosion type identifies the dominant mode of sediment transport at each site. Mass wasting was the dominant erosion type at a site if there was evidence of slope failure. Surface erosion was the dominant process if any evidence of sheet flow was present. Rill and gully are essentially the same erosional type and differ only in the depth of their incision into the soil. Here, a rill is an incision into soil caused by the overland flow of water where the width of the incision is generally greater than the depth. A gully is also an incision into soil caused by overland flow, but the depth is much significantly greater than the width. Ravel is the transport of sediment by rolling, bouncing, or sliding down the slope. Slopes with noticeable volume of fine unconsolidated sediment at their bases and no noticeable transport conduits have ravel as the dominant erosion type. Wave erosion and sapping are both caused by wave action. A site has wave action as its dominant erosion type if wave terraces are present or sediment was present in the water adjacent to the bank, but if wave action formed an overhang of the shoreline then the dominant erosion type was sapping. Other dominant erosion types were present along the shoreline of Shasta Lake, but the criterion for identification was based solely at the discretion of the observer.

Erosion severity is a qualitative measure of the rate and total volume of erosion. A site with a high erosion severity contains abrupt erosional features with physical evidence of a consistently high erosion rate. In short, a high erosion severity feature is an erosional feature that is actively eroding and enlarging and has not reached a state of equilibrium. A site with medium erosion severity has well defined erosional features where the activity is episodic or beginning to stabilize. Generally, moderate erosion features are not enlarging. For example, a slope with partially vegetated gully would be designated as medium erosion severity. Low erosion severity sites are sites with defined erosional features that are near a state of equilibrium. For example, a shoreline that is armored by bedrock or a site that has a slope gradient less than 30 percent are considered a low erosion severity sites.

Slope angle is a measure of the percent slope from the edge of water to the highest elevation of the site. Slope angle was measured using hand held clinometers by sighting the top of the slope from the edge of water at the time of survey.

Slope break type is categorization of the type of slope that was formed adjacent to the shoreline due to the seasonal water-level fluctuations within Shasta Lake. An oversteepened slope break is a slope where wave action or inundation has eroded the bases of a slope and caused a subsequent head-cut or upslope migration of the dominant erosional process. An undercut slope break is a slope that has been eroded by wave action or inundation causing an overhang within the slope. Any slope showing features of oversteepened and/or undercut slopes was designated in both categories.

Material type and the relative amount of slope armor were recorded for sites with un-eroded slopes. Initially, the dominant material size that composed the slope was determined by ocular assessment and recorded as one of three categories: bedrock, boulder-cobble, or soil. The aerial extent of area of the slope that was covered by the dominant material was determined by ocular assessment and recorded as one of three categories: 0-30 percent; 31-70 percent; and >71 percent.

For sites with eroded slopes, the height of the eroded slope was measured from the bottom of the near shore zone (i.e., wave cut bank) to the highest point on the slope where evidence of erosion is visible using a survey tape. Each site was then recorded as one of three slope height categories: 0-3 feet; 3-6 feet; or 6 feet.

The aerial extent and density of vegetative cover was determined for each site using relative vegetative cover classes of: sparse; moderate; or dense. These categories were a qualitative measure of the proportion of vegetation cover to the amount of area at each site. The extent of vegetation cover was determined by assessing how much native surface could be seen if the observer looking down at the site surface from above the canopy. The type of vegetation was not taken into consideration when determining the amount of vegetation cover. If less than 20 percent of native surface could be seen, the site had dense vegetation cover. If between 20-80 percent of the native surface could bee seen, the site had moderate vegetation cover. If more than 80 percent of the native surface could be seen, the site had sparse vegetation cover.

2.2.2 Shoreline Erosion Plot Survey Methods

Shoreline profile surveys of selected areas along the shoreline of Shasta Lake were completed to characterize and directly measure existing and potential erosion volume. Erosion sites were selected to provide representation of the three erosion severity classes (low, moderate and high) mapped during the of Shasta Lake shoreline erosion inventory.

In 2002 and 2004, surveys were conducted on Big Backbone and Squaw Creek Arms using standard survey instruments (auto level, stadia rod, and survey tape). In 2007, additional surveys were completed on the Main Body East, Main Body West, McCloud, Pit, and Sacramento River arms using a Nikon 522 Total Station. The total station is accurate to +/- 0.01 feet at 500 feet and +/- 0.1 feet at 1000 feet. Both survey methods surveyed known local control points to ensure horizontal and vertical accuracy. The 2004 surveys also established benchmark elevations or control points using a sub-foot accuracy Trimble GPS and constructed permanent survey monuments for future use.

Up to two profiles were surveyed at each site to construct an average topographic representation of each site. Benchmark monuments were established, consisting of about one meter lengths of rebar driven into the ground. The benchmarks are assumed to represent the maximum reservoir elevation (1,070-feet mean sea level, NAVD88) in the absence of wind-generated waves. Transect distances were recorded along the profile sections, upslope to an estimated position twenty vertical feet above the benchmark (to correspond to the 1,090-feet elevation considered in the SLWRI), and downslope to the water surface. In 2004, several profiles in both Big Backbone Creek and Squaw Creek arms were re-surveyed from the benchmark monuments to the reservoir surface. The reservoir surface elevations recorded by the Reclamation gage at Shasta Dam at the time of the re-surveys were used to back-calculate the benchmark elevations for the re-surveyed profiles. For those profiles that were not re-surveyed, benchmark elevations were assigned based on the mean benchmark elevations of the re-surveyed profiles. Big Backbone Creek profiles were assigned the Big Backbone Creek mean benchmark elevation; Squaw Creek profiles were assigned the Squaw Creek mean benchmark elevation.

2.3 Existing and Potential Shoreline Erosion Calculations

Several steps were required to determine existing shoreline erosion volumes, rates, and erosional rates per acre at each site surveyed. The first step was to plot the existing slope surfaces from the erosion site surveys. Standard trigonometric survey calculations were performed to derive profile distances and elevations recorded from the surveys conducted in 2002 and 2004. Profile distances and elevations were directly recorded from the Nikon Total Station during the 2007 surveys. All horizontal distances were referenced from an arbitrary zero value at the benchmark, with down-slope (towards lake) distances assigned negative values and upslope distances assigned positive values. The length of the existing slope surface was surveyed from above the maximum anticipated water level (1,090 feet) down to the water level of the lake. Subsequently, the length and angle of the existing slope was estimated and projected down to a drawdown level of 1,020 feet.

The second step was to determine the projection of the pre-inundation slope surface. Calculations were made to generate curves representing estimated ground surfaces before inundation and wave erosion using two key assumptions:

- The height of the shoreline bank is representative of the depth of weathered material that was eroded following inundation.

- The weathered depth exposed on the shoreline bank remains uniform up- and down-slope. Consequently, the slope of the present wave-eroded shoreline bank is parallel to the slope of the pre-inundation surface. This suggests that erosion depth may be modeled based on the present shoreline bank height.

The third step was to calculate the volume of sediment removed since the inundation of the slope at each erosion site. The cross-sectional area was calculated between the existing surface and the projected pre-inundation surface along the transect line and between the 1,020 foot drawdown level and the existing full pool elevation of 1,070 feet. The actual cross-sectional area was calculated for each site using a built-in area-under-the-curve function available in Grapher™ software.

The cross-sectional area was used to calculate the total erosion volume produced at each erosion site under existing conditions. Each erosion transect was assigned a width of half of the transect length between the measured water level and the highest existing shoreline (1,070 feet). This designation standardized all of the erosion sites by creating an erosion plot area that is directly proportional to the length of the survey transect. The cross-sectional area was multiplied by the width of each erosion site to calculate the total eroded volume of sediment for the period of time since the reservoir was constructed, with respect to each site.

The existing annual shoreline erosion volume (in cubic yards per year) was calculated by dividing the total volume of eroded sediment by the number of years since the site was initially inundated. Shasta Lake was fully inundated about 60 years ago, so yearly erosion rates were determined by dividing total volume of sediment eroded at each site by 60 years. This model acknowledges that erosion rates most likely did not remain constant over the 60 year period, therefore the 15 year erosion rate was calculated as well, since most of the erosion occurs during time step one of the conceptual model. This also helps account for the episodic nature of shoreline erosion that has high annual variability.

The erosion rate was also calculated for each site (in cubic yards per acre per year). The erosion rate was calculated for each erosion site by dividing the yearly erosion rate by the area (in acres) of its erosion plot. In this manner, an existing unit erosion rate could be applied to other shoreline erosion inventory sites with similar attributes to estimate existing shoreline erosion within the footprint of Shasta Lake.

The potential shoreline erosion volumes and rates were calculated using the same assumptions that were used to calculate the existing rate. A critical assumption is that the landform upslope of the 1,070 foot elevation is similar to the slopes subject to erosion below this point. The transects that depicted the existing and estimated original ground surfaces from the maximum drawdown level (1,020 feet) to the projected highest shoreline (1,090 feet) were also used to calculate potential shoreline erosion. For transects that were used to calculate potential shoreline erosion, further calculations were made to generate curves that represented the subsurface layer below the present ground surface. This analysis assumes that the subsurface layer would be exposed after a twenty foot rise in the maximum reservoir water surface level (1,090 feet) and shoreline forming events. In most cases, a parallel model based on the vertical angle of the shoreline bank was employed. This means that the current angle where the bank meets the water surface will eventually be the same angle formed on the new inundated surface. A problem with this model involved some sites where a twenty foot rise in reservoir levels would completely inundate the site (the maximum upslope ground surface elevation was less than twenty feet above the present highest shoreline). In this case, it was assumed that the volume of future erosion could be based on the shoreline height, up to the highest ground surface elevation of the profile.

After the estimated subsurface layer was plotted against the existing ground surface, the annual volume of sediment eroded from the newly inundated slope was calculated. The cross sectional area was calculated between the existing surface and the subsurface along the transect line and between the highest existing shoreline level (1,070 feet) and projected highest shoreline level (1,090 feet). The actual cross-sectional area was calculated for each site using Grapher™. Each erosion site was assigned a width of ½ the transect length. The cross-sectional area was multiplied by the width of each erosion site to calculate the total predicted volume of sediment erosion after inundation of the slope to the projected highest shoreline.

The potential shoreline erosion rates (in cubic yards per year) were determined by dividing the total volume of eroded sediment by the number of years since the site was inundated. Two time spans, 15 and 60 years respectively were used to calculate the yearly erosion rates. These spans were selected to provide a range of erosion rates based on the relative rate at which a slope erodes to reach a state of equilibrium.

The unit potential erosion rate was also calculated for each site (in cubic yards per acre per year). The unit erosion rate was calculated for each erosion site by dividing each respective yearly erosion rate (15 or 60 years) by the area (in acres) of its erosion plot. In this manner, an existing unit erosion rate could be applied to other shoreline erosion inventory sites with similar attributes to estimate potential shoreline erosion within the footprint of Shasta Lake.

In an attempt to characterize the potential erosion volume and rate for 52 erosion plot survey sites that are based on the physical or erosional features of any area of shoreline within Shasta Lake, the potential shoreline erosion rates from each erosion plot were compared to the categorical data collected from the shoreline erosion reconnaissance inventory. Individual categories of physical and erosional features were plotted against potential erosion rates to determine if a strong correlation was present. Erosion severity and eroded slope height had the strongest correlation of all categories. This relationship was used to assign each erosion plot to one of eight categories based on the combined data of erosion severity and eroded slope height. The combined potential erosion rates from the plots are illustrated in Figure 2 for both time steps. New potential erosion rates (cubic yards per year) were assigned to each category by adding the average potential erosion rate to half of the standard deviation and rounding to the nearest increment of 50 feet. Low severity sites were all assigned the same potential erosion rates because there were no low erosion severity sites with an eroded wave height above three feet, and it is assumed that eroded slope height would have little impact on low erosion severity slopes.

Using this relationship, potential erosion rates can now be assigned to any of the shoreline survey reconnaissance sites based solely on its erosion severity and eroded slope height values. This allowed for an estimation of total volume of sediment eroded by arm and for the entire lake.

Chapter 3 Results and Discussion

3.1 Climate Data

3.1.1 Precipitation

Shasta Lake and the surrounding landscape experiences a Mediterranean-type climate with wet mild-winters and hot dry summers. The average annual precipitation measured at Shasta Dam is 64.1 inches. 80 percent of the precipitation occurred between the months of November and March. About 30 percent of the annual precipitation falls during September through December, and the remaining 50 percent falls between January and March. Large extended precipitation events are frequent during the wet months. Between the years of 1995 and 2007, the largest annual recorded 24-hour precipitation events ranged between 8.3 inches and 3.5 inches with a median event of 4.7 inches.

Based on existing historic climate data, it is assumed that enough precipitation falls to saturate most of the soils on the slopes within and adjacent to Shasta Lake by the end of December. A majority of the annual precipitation and large storm events occur after this time, between January and March, when the soils are saturated (Table 3-1). This suggests that large amounts of surface runoff and subsequent surface erosion occur during large storm events. Using this premise, it is assumed that a majority of the surface erosion is caused by large storm events between the months of January and March.

Table 3-1. Shasta Lake Average Annual and Monthly Precipitation Summary

Month	Average Precipitation (inches)	Percent of Total
January	11.47	18%
February	10.76	17%
March	10.79	17%
April	4.18	7%
May	2.8	4%
June	1.25	2%
July	0.26	0%
August	0.42	1%
September	1.63	3%
October	2.97	5%
November	7.86	12%
December	9.01	14%

3.1.2 Wind

Average annual wind speeds and wind directions were calculated for Shasta Lake for the period of 01/01/2003 to 12/31/2007. All calculations were made using historical data from a Redding, California weather station (RED) maintained by the U.S. Forest Service. Data from the RED station is used because it is the closest weather station to Shasta Lake that records wind speed and direction. The data used from the RED station are assumed to be representative of the reservoir, but variation in the average wind speeds and direction of travel are expected due to differences in local topography. Initially, raw wind direction data was given as a wind source direction, but in the summaries, 180 degrees was subtracted from the averages to calculate a direction of travel.

The median of the average annual wind speed for the study period is 6.1 mph, and the median annual direction of wind travel is 36 degrees (southwest to northeast). Average annual wind speeds vary slightly and range between 5.6 miles per hour and 6.4 miles per hour. The average direction of wind travel has some variation ranges between 33 and 70 degrees.

Annual average wind speeds and wind directions are plotted on a wind chart (Figure 3-1) to further characterize the wind patterns of the study area. Wind speeds are divided into two categories based on a median annual wind speed of 6.1 mph. The orientation of the polygons on the chart represents the direction of travel within a range of 5 degrees. The relative length of each polygon (from the center of the chart) represents the number of years, or frequency, that the average annual direction of wind travel was within a specific 5 degree range. Within the wind chart, frequency is expressed as a percentage of the entire data set. The corresponding average annual wind speed is also projected and represented as smaller shaded polygons within the larger wind travel polygons. Their relative length, compared to the larger polygon represents the frequency at which a specific wind speed class coincided with the direction of wind travel.

The wind chart clearly shows that the dominant direction of wind travel is from southwest to northeast. From this trend, the assumption is made that the southwest facing shorelines of Shasta Lake will receive most of the energy produced by wind waves. However, one year within the data set varied noticeably from the median direction of wind travel. This could indicate that dominant wind patterns fluctuate regularly, but this assumption is not made here due to the limited size of the data set. In addition, there doesn't appear to any correlation between the direction of wind travel and wind speed within the data set.

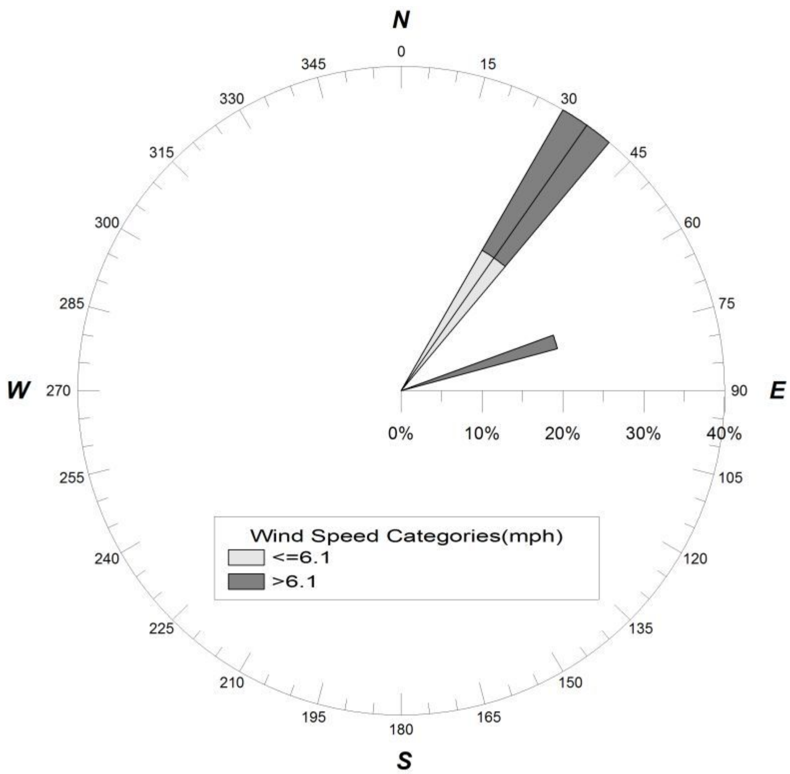


Figure 3-1. Wind Chart Showing Average Annual Azimuth of Wind Travel by Frequency Percentage and Proportionate Wind Speed Category for Redding, California Weather Station for 2003 – 2007

3.2 Shoreline Erosion Inventory Results

A total of 1,538 shoreline erosion reconnaissance sites were surveyed within the seven lake arms of Shasta Lake between 2002 and 2007 (Table 3-1). Site locations were defined in the field at any location where visual evidence of erosion was observed along the entire shoreline of Shasta Lake (420 miles). Additionally, the number of sites inventoried within each arm is proportional to the size of each arm relative to the footprint size of Shasta Lake. Of the 1,538 sites surveyed: 363 sites (about 24 percent of all inventoried sites) are located within the Main Body East Arm; 313 sites (20 percent) are located within the Sacramento River Arm; 301 sites (20 percent) are located within the McCloud River Arm; 207 (13 percent) sites are located within Pit River Arm; 128 sites (8 percent) are located within the Big Backbone Creek Arm; 115 (7 percent) sites are located within the Squaw Creek Arm; and 111 sites (7 percent) are located within the Main Body West Arm of Shasta Lake.

Site locations were selected to characterize the erosional features of each arm and Shasta Lake. Data was gathered at each site for the following erosional features: erosion severity, slope height, erosion activity, dominant erosion types, slope angle, slope break type, material type, slope armor, and vegetative cover (Table 3-1). At least one categorical value was recorded for each erosional feature, but multiple values were recorded for erosion activity, dominant erosion types, and material types. This redundancy occurs because more than one type of each category can be present at each site. Here, it is assumed that the summarized data of the shoreline erosion reconnaissance inventory accurately represents the shoreline features of Shasta Lake.

Erosion severity and slope height are related. If the frequency of categorical erosion severity sites is compared to the frequency of categorical slope height sites, the relationship is apparent. The data shows a total of 752 sites (or 49 percent) with low erosion severity, and 716 sites (47 percent) with a slope height of 0 to3 feet. A total of 520 sites (34 percent) have moderate erosion severity, compared with 512 (33 percent) sites that have a slope height of 3 to 6 feet. Additionally, 264 sites (17 percent) have high erosion severity, and 308 sites (20 percent) have a slope height of greater than 6 feet. Not only are the frequencies of the categorical features related, but they often occurred in discrete pairs at each site. This suggests that erosion severity, and possibly the erosion rate, increase as bank height increases. Erosion severity and slope height also correlated with measured erosion rates, and erosion severity and slope height combinations were the variables used to predict erosion rates.

Nearly all inventoried sites have at least one feature that is chronically eroding. For example, 1514 sites (98 percent) have evidence of chronic erosion activity. Additionally, 230 sites (15 percent) have evidence of episodic erosion activity, and 29 sites (2 percent) have evidence of historic erosion activity. The data indicate that the shoreline of Shasta Lake is actively eroding.

Wave erosion is the dominant erosion type of the sites inventoried, and dry ravel is present at nearly half of the sites. Evidence of wave action is recorded at 1250 sites (81 percent). Dry ravel is a dominant form of erosion at 742 (48 percent) sites. Mass wasting is evident at 339 sites (22 percent), and 278 sites (18 percent) have surface erosion as dominant form of erosion. Gullies, rills, or other forms of erosion are actively eroding the shoreline 37 sites (2 percent)

Nearly all (89 percent) of the sites of have a slope less than 60 percent, with 793 sites (52 percent) having a slope angle between 31 percent and 60 percent. Slope angles between 0 percent -30 percent are present at 566 sites (37 percent), but 177 sites (12 percent) have a slope angle greater than 60 percent.

There appears to be no visible trend with regards to the type of slope break present on the slopes of the sites. An oversteepened slope break occurs at 636 sites (41 percent), and 316 sites (21 percent) have an undercut slope break. However, 550 sites (36 percent) have examples of both types.

A soil horizon covers nearly all sites inventoried; 1379 sites (90 percent) of the sites have soil covering the slope. A cobble to boulder sized substrate covers 126 sites (8 percent), and 50 sites (3 percent) are exposed bedrock slopes.

There is limited amount of armor present on the shoreline slopes at the sites. Armor covers 0 percent to 30 percent of the surface area at 1381 sites (90 percent). A small portion, 152 sites (10 percent), have 31 percent -70 percent of the surface covered with slope armor, and only 3 sites have more than 70 percent of the surface armored.

Most (82 percent) of the sites have moderate or dense vegetation. Moderate vegetation cover occurs at 941 sites (61 percent), while dense vegetation covers 327 sites (21 percent). Sparse vegetation cover occurs at 266 sites (17 percent).

For a typical site, the average shoreline has less than a 60 percent slope which is covered by a soil horizon, moderately vegetated, with limited amounts of shoreline armor. Chronic erosion occurs on the slope due to wave action at the shoreline, and dry ravel occurs on the slopes above after drawdown of the water level. Erosion creates a slope height of 0 to 3 feet above the maximum water level of the lake. Even though erosion does occur, the nature of the erosion on the slopes causes erosion severity to be low.

3.3 Existing Shoreline Erosion Calculations

There are over 420 miles of existing shoreline around Shasta Lake, and about 50 percent of the shoreline has a low erosion severity. The remaining shoreline has moderate (35 percent) to high (15 percent) erosion severity. Most of the shoreline that is exposed during routine drawdown periods (i.e., drawdown zone) has been subject to substantial erosion and there is very little soil remaining after more than 60 years of reservoir operations.

The measured volume of existing shoreline erosion is summarized for the erosion inventory sites located around the entire reservoir. The measured shoreline erosion rate over the past 60 years, averages about 90 cubic yards per acre per year, per site. Within the first 15 years of dam construction (i.e., 1960) the average rate was likely about 360 cubic yards per acre per year. Most of the shoreline has reached a steady state of erosion similar to the uplands and erodes at a rate between 30 and 90 cubic yards per acre per year. Areas with high erosion severity that continue to migrate upslope, some of which are already above the 1,090 foot contour, are still eroding at rates greater than 400 cubic yards per acre per year.

The highest rate of shoreline erosion is occurring in the Sacramento River arm. For time step one (i.e., first 15 years), the average erosion rate for this arm was about 900 cubic yards per acre per year. For time step two the average erosion rate has decreased to about 230 tons per acre per (i.e., last 50 years). The McCloud River and Pit River Arms have the lowest rate of erosion at about 180 tons per acre per year for time step one, and about 45 tons per acre per year for time step two.

Presently, the shoreline erosion analysis indicates that at least half of the shoreline is in quasi-equilibrium and is in time step three of the conceptual model (Figure 2-2). For these stable areas time step two likely lasted between 15 and 30 years. About one quarter of the shoreline continues to erode at moderate rates. The remaining quarter of shoreline is eroding at very high rates. The shoreline erosion survey results suggest that the primary causes of continued shoreline erosion appear be oversteepened deep erodible soils where the slope shear strength is reduced by toe erosion and vegetation removal by fire and anthropogenic activities. The erodible soil types tend to be Holland Family, characterized as deep, with Fine-loamy texture and a meta-sediment parent material. The primary external trigger of this erosion is continued reshaping of the slope toe by waves and surface runoff. The combination of steep and tall banks formed by erodible soils limit the slope stability of these areas.

Erosion inventory results indicate that wave action was causing near shore and drawdown zone erosion at 87 percent of the sites. These data suggest that the prevalence of wave erosion appears to be independent of aspect and location within the reservoir. The severity of wind erosion appears to be greatest on shoreline facing south-west. During full pool conditions (i.e., May – June) winds tend to blow at above average speeds in a south-westerly direction (Figure 3-1). Sites with deep erodible soils that face west and south frequently have mass wasting features where wave erosion removes lateral support along the toe of the slope. Most of the mass wasting features are shallow debris slides or vertical bank collapse. Some of these features have an erosion rate greater than 1,000 cubic yards per acre per year.

The shoreline erosion plot survey results were summarized and analyzed to quantify the historic and existing rate of shoreline erosion and predict the future rate. Data from the erosion plot sites were used to calculate the existing eroded volume of shoreline in the drawdown zone. For each erosion plot, a survey form was completed, and the results were analyzed using categorical statistical methods to determine which variables measured as part of the survey could be used to predict the rate of erosion where erosion plot surveys were not completed. This analysis found that bank height and erosion severity observations tended to correlate with the measured erosion volume. The other measured parameters did not have enough variability to provide a predictive relationship. For example, 87 percent of the sites have waves as a dominant erosion mechanism and most of the bank material was classified as soil. Bank height and erosion severity were concatenated to produce a lookup table of measured erosion rates. For all the survey sites this relationship was used to estimate total shoreline erosion as described below.

3.4 Potential Shoreline Erosion Calculations

Inundation of additional lands surrounding Shasta Lake could result in increased soil erosion, mass wasting, and subsequent sedimentation of the reservoir and the tributaries that are influenced by fluctuating lake levels. Shoreline erosion commonly contributes a large portion of the sediment to reservoirs (Morris and Lan 1997). Sediment sources from receding shoreline contributes to reservoir sedimentation, can degrade water quality, result in loss of soil productivity, and impact infrastructure, cultural sites, and wildlife habitat.

Within the framework of the shoreline erosion conceptual model for Shasta Lake, this analysis used direct measurements of shoreline erosion to predict the potential shoreline erosion volume and the average annual erosion rate for the entire shoreline for the 15 year and 60 year time periods. In addition, potential shoreline erosion was calculated for three different dam raise alternatives: Comprehensive Plan (CP)1 (1,070 feet – 1,080 feet); CP2 (1,070 feet – 1,084 feet); and CP3 (1,070 feet – 1,090 feet) for each time period. The maximum raise of 20 feet was calculated first and these results were used to calculate erosion from the other alternatives. The eroded volume was proportioned based on the area of shoreline inundated by the CP1 and CP2 alternatives. Table 3-2 lists the 15 year time period shoreline erosion volume calculation results by Lake Arm and erosion severity risk. Table 3-3 lists the results for the 60 year time step.

Table 3-2. SLWRI Potential 15-Year Shoreline Erosion Volume Calculations Between the 1,070 feet – 1,090 Feet Contours by Lake Arm and Erosion Severity Risk

Erosion Severity	Sacramento River Arm	McCloud River Arm	Mainstem East Arm	Pit River Arm	Squaw Creek Arm	Big Backbone Creek Arm	Mainstem West Arm	Total Erosion	% of Total Shoreline Erosion
High	47,176	34,782	27,102	18,900	12,487	16,354	22,965	179,767	23%
Moderate	116,561	81,595	88,809	69,026	39,393	33,110	19,107	447,601	58%
Low	41,815	23,932	36,190	11,099	16,305	6,725	3,623	139,689	18%
Total Annual Erosion	205,552	140,309	152,102	99,026	68,184	56,188	45,696	767,056	100%
% of Total Shoreline Erosion	27%	18%	20%	13%	9%	7%	6%	100%	

Key:
SLWRI = Shasta lake Water Resources Investigation

Table 3-3. SLWRI Potential 60-Year Shoreline Erosion Volume Calculations by Lake Arm and Erosion Severity Risk Assuming no Vegetation Treatment

Erosion Severity	Sacramento River Arm	McCloud River Arm	Mainstem East Arm	Pit River Arm	Squaw Creek Arm	Big Backbone Creek Arm	Mainstem West Arm	Total Erosion	% of Total Shoreline Erosion
High	11,204	8,419	5,970	4,308	3,150	3,722	5,004	41,777	19%
Moderate	29,176	19,416	19,958	18,752	10,768	8,527	3,698	110,295	51%
Low	18,273	11,468	15,398	6,613	7,295	3,513	1,703	64,262	30%
Total Annual Erosion	58,653	39,302	41,326	29,673	21,213	15,762	10,404	216,333	100%
% of Total Shoreline Erosion	27%	18%	19%	14%	10%	7%	5%	100%	

Key:
SLWRI = Shasta lake Water Resources Investigation

Three different vegetation treatments have been proposed, common to all action alternatives: no treatment; overstory removal; and complete vegetation removal. This model assumes that the erosion rate will be higher for areas with partial or complete vegetation removal. Shoreline areas with overstory removal are assumed to erode 25 percent faster than no treatment areas, and areas with complete vegetation removal area assumed to erode 40 percent faster than no treatment areas. For areas with vegetation removal the shear strength of a treated hillslope will be less than a fully vegetated slope, and the treated slope is predicted to erode faster during the first time step of the conceptual model.

Assuming the available vegetation removal prescriptions between the 1,070 feet – 1,090 feet contours, for the first time step (i.e., 15 years after raising Shasta Dam) there will be about 767,000 cubic yards per year of shoreline erosion (Figure 3-2). After about 15 to 20 years, depending on water year type and operational variability, the expanded shoreline will develop, and to varying degrees stabilize (Figure 3-3). The total reservoir erosion is predicted to decrease by 70 percent between 15 and 60 year after raising the dam. The wetter the climate cycle the more rapid the shoreline is predicted to form. This analysis also calculated the 15 year erosion volume using the prescribed vegetation treatments and modeled higher erosion rates for shoreline with partial and complete vegetation removal.

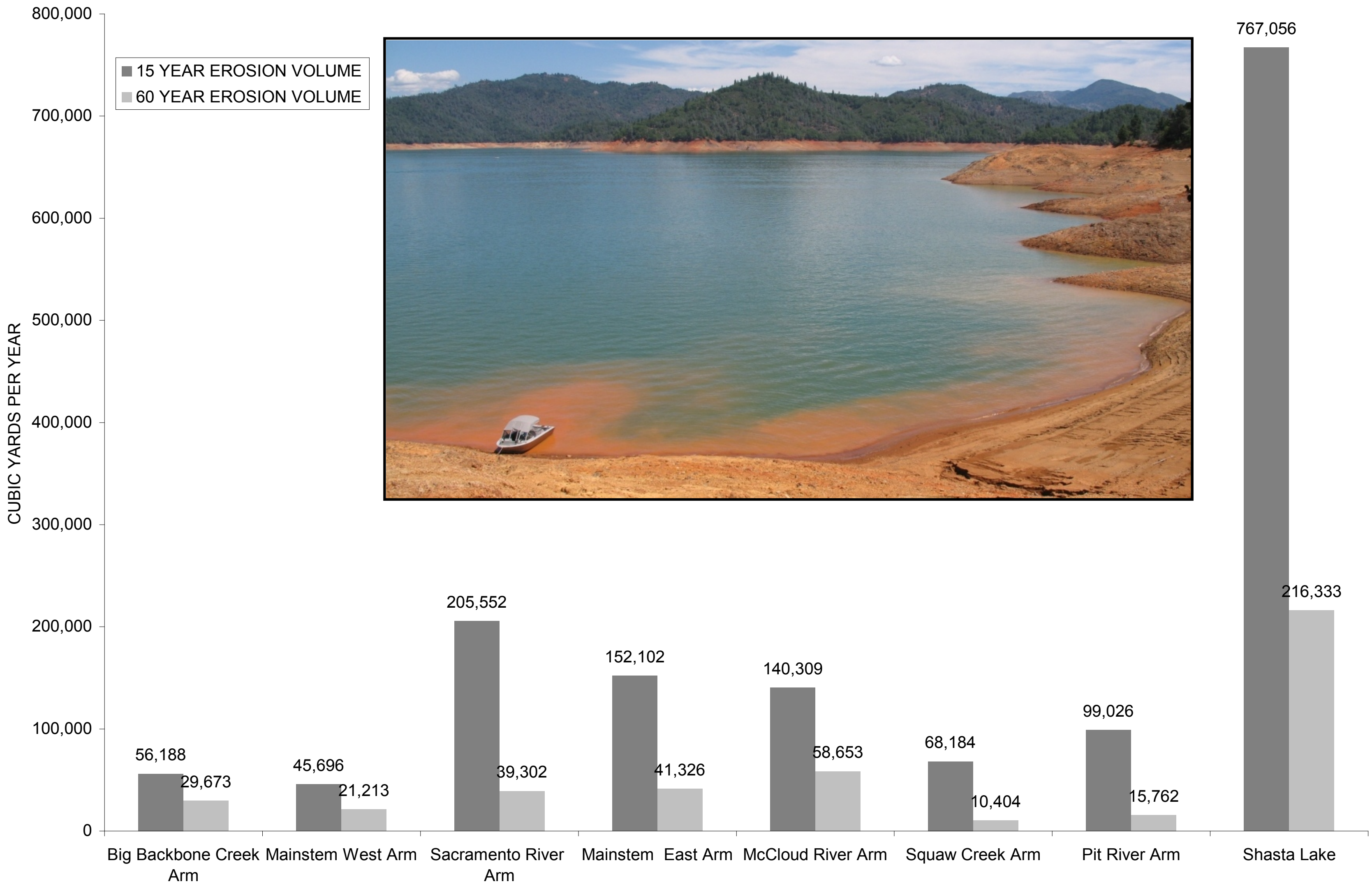


Figure 3-2. SLWRI 15- and 60-Year Potential Shoreline Erosion Volume Calculation Results by Lake Arm for the Shoreline Between the 1,070 feet – 1,090 Feet Contours

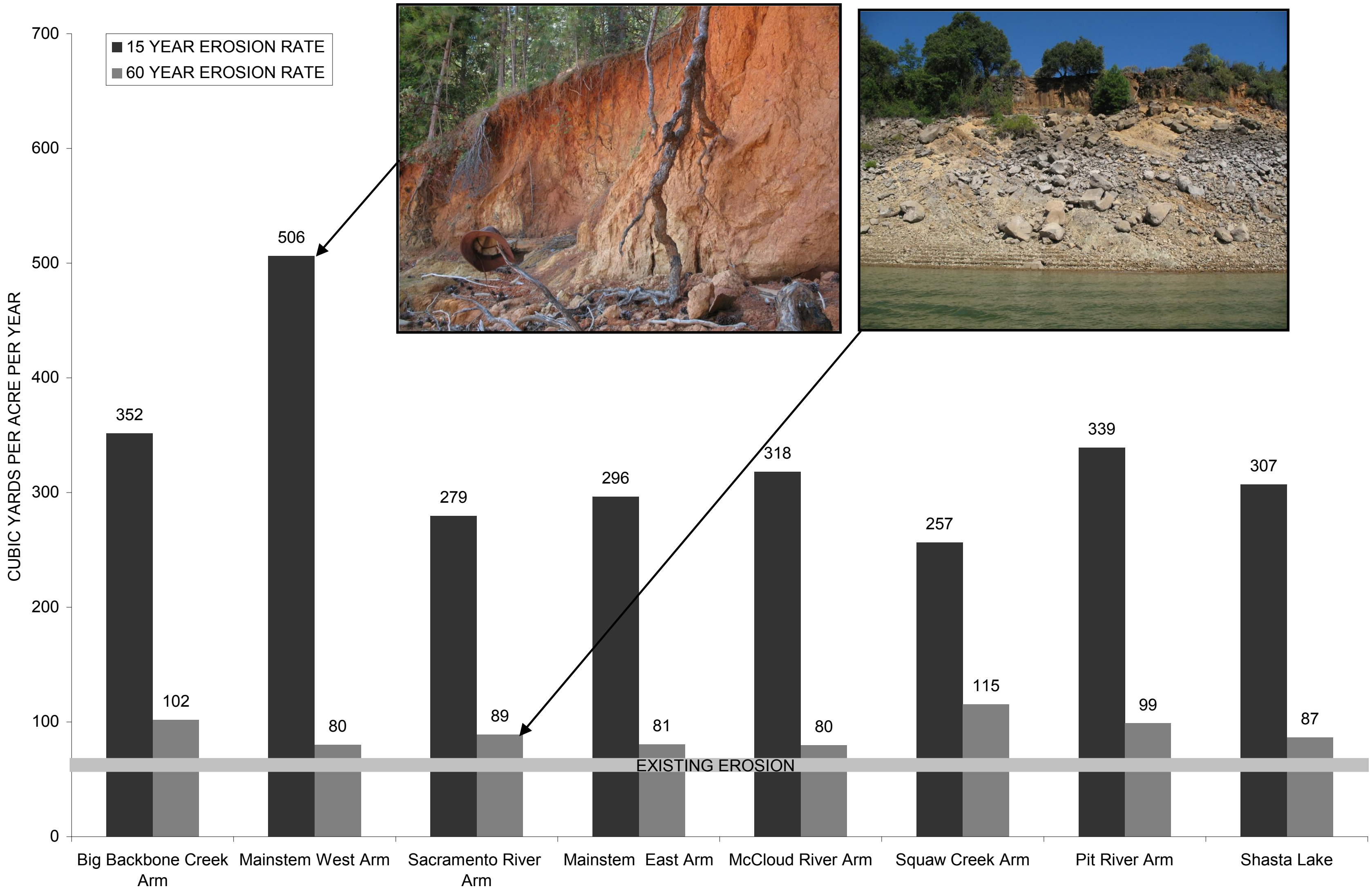


Figure 3-3. SLWRI 15- and 60- Year Potential Shoreline Erosion Rate Calculation Results by Lake Arm for the Shoreline Between the 1,070 feet – 1,090 Feet Contours

Overall, a substantial portion of the shoreline is rated as having moderate erosion severity and most arms follow this trend. The Mainstem West Arm and the Pit River Arm are the exceptions, where over half of the Mainstem West has a high erosion rating and the Pit River has predominantly low to moderate rates. Shoreline erosion volume calculation results suggest that the total amount of erosion is directly a function of the shoreline area inundated independent of the severity of erosion. A positive linear relationship was found between the shoreline area inundated and the predicted erosion volume for the CP3 raise where:

$$y = 260.9x + 16{,}482$$

$$R^2 = 0.977$$

The model predictions indicate that the Sacramento River, McCloud River, and Mainstem East Arms will produce about half of the shoreline erosion. For the second time step (i.e., up to 60 years), the predicted annual shoreline erosion for the reservoir is 216,000 cubic yards per year (Figure 3-2). The long term erosion estimates reflect the first and second time steps of the shoreline erosion conceptual model where most of the erosion occurs in the first 15 years. After 60 years this model assumes that most of the shoreline has reached a state of equilibrium.

The highest rates of erosion are predicted to occur for the first 15 years after raising Shasta Dam (CP3, 1,090 feet) with a reservoir average of about 300 cubic yards per acre per year (Figure 3-3). The Mainstem West Arm has the highest predicted rate of erosion for the first time step. The predicted erosion rates for Big Backbone Creek, Pit River, and McCloud River Arms are greater than the reservoir average (Figure 3-3).

Shoreline erosion would increase as a result of implementing CP1, CP2, or CP3. For the first 15-years after raising the dam, the average rate of shoreline erosion would increase substantially. This increase varies between 90 cubic yards per acre per year to about 300 cubic yards per acre per year. For the first time step (i.e., 15-years), the total average annual volume of potential shoreline erosion from CP3 is about 767,000 cubic yards per year (Figure 3-2). Within 60 years of raising the dam, the average annual volume is predicted to decrease to 216,000 cubic yards per year (Figure 3-2).

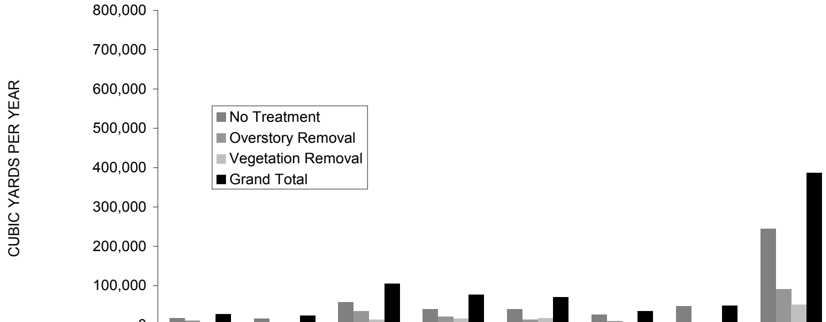
Sediment delivery from shoreline erosion would likely be greatest in the Sacramento River Arm, Main Body East Arm, and McCloud River Arm. These three arms are predicted to deliver more than 66,000 cubic yards per year for the first 15-years after raising the dam (Figure 3-2). Within 60 years of raising the dam, the average rate for these arms is predicted to decrease to 19,000 cubic yards per year (Figure 3-2). The Mainstem West Arm and Backbone Creek Arm are predicted to have the lowest shoreline erosion rates, a 15-year average annual potential erosion volume of less than 26,000 cubic yards per year. The

Pit River Arm is predicted to produce about 50,000 cubic yards per year and the Squaw Creek Arm about 35,000 cubic yards per year (Figure 3-2).

Assuming the available vegetation removal prescriptions between the 1,070-foot and 1,080-foot contours, for the first time step (i.e., 15-years after raising Shasta Dam) there would be about 421,000 cubic yards per year of shoreline erosion (Figure 3-2). After about 15 to 20 years, the new shoreline would develop and begin to stabilize (Figure 2-2). The total reservoir erosion is predicted to decrease by 70 percent between 15 and 60 years after raising the dam. The wetter the climate cycle, the more rapidly the shoreline is predicted to form.

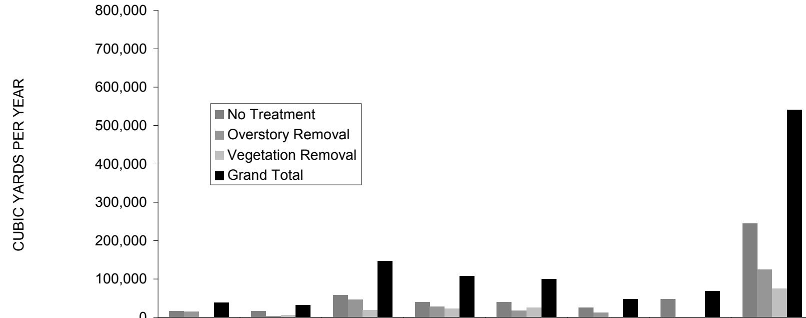
The analysis also calculated the 15-year erosion volume using the prescribed vegetation treatments and modeled higher erosion rates for shoreline with partial and complete vegetation removal (see Methods and Assumptions above). Most of the shoreline would not have vegetation clearing which is about 60 percent of the total predicted shoreline erosion. The Big Backbone Creek, Squaw Creek, and Pit River Arms would have very little vegetation removal. The Mainstem West, Sacramento River, Mainstem East, and McCloud Arm would have substantial amounts of vegetation removal, which would result in higher short-term erosion rates. For these arms, areas treated by vegetation removal represent about half of the total predicted erosion for each alternative (Figure 3-4).

CP-1



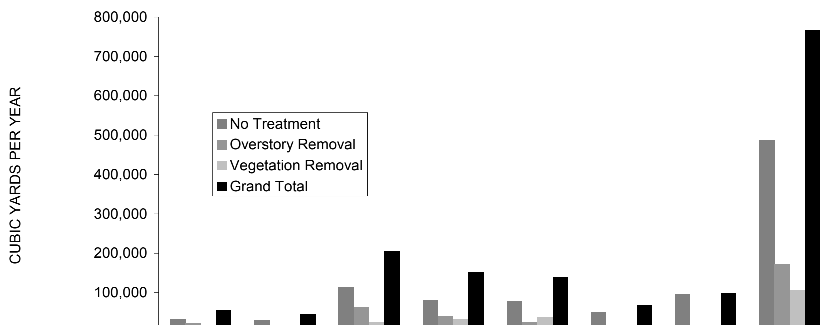
	Big Backbone Arm	Mainstem W Arm	Sac Arm	Mainstem E Arm	McCloud Arm	Squaw Arm	Pit Arm	Total Erosion
No Treatment	16,585	16,255	58,004	40,225	39,555	25,897	47,727	244,248
Overstory Removal	10,839	2,650	34,289	20,523	13,151	9,147	639	91,239
Vegetation Removal	0	4,324	12,820	15,537	17,916	0	813	51,410
Grand Total	27,425	23,229	105,113	76,285	70,622	35,043	49,179	386,897

CP-2



	Big Backbone Arm	Mainstem W Arm	Sac Arm	Mainstem E Arm	McCloud Arm	Squaw Arm	Pit Arm	Total Erosion
No Treatment	16,585	16,255	58,004	40,225	39,555	25,897	47,727	244,248
Overstory Removal	15,195	3,679	46,686	28,234	17,942	11,730	901	124,367
Vegetation Removal	0	6,403	18,476	22,921	25,882	0	1,175	74,857
Grand Total	38,599	32,491	146,390	107,568	99,585	48,117	69,000	541,750

CP-3



	Big Backbone Arm	Mainstem W Arm	Sac Arm	Mainstem E Arm	McCloud Arm	Squaw Arm	Pit Arm	Total Erosion
No Treatment	34,168	31,458	115,469	79,966	77,983	51,626	96,032	486,702
Overstory Removal	22,020	5,054	63,708	39,524	25,046	16,558	1,338	173,248
Vegetation Removal	0	9,183	26,375	32,612	37,280	0	1,656	107,106
Grand Total	56,188	45,696	205,552	152,102	140,309	68,184	99,026	767,056

Figure 3-4. SLWRI 15-Year Potential Shoreline Erosion Volume Calculation Results for CP1, CP2, and CP3 by Lake Arm

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Chapter 4 References

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